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GROUNDWATER STUDY AT NANTICOKE ASH LAGOON
PART I: PHYSICAL HYDROGEOLOGY

Report No 89-185-K

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ABSTRACT

A hydrogeological investigation was initiated in the fall of 1986 within and around the existing Nanticoke TGS fly ash disposal area. The objective of this study was to determine the environmental impact of fly ash disposal on the groundwater regime beneath the ash lagoon. The results of the study could be applied to the design and siting of future FGD waste disposal operations. The field program consisted of installing 6 "piezometer nests" both within and outside the fly ash disposal area. These piezometers were then used for hydraulic conductivity testing of the clay overburden and for long-term monitoring of water levels to determine equilibrium hydraulic heads and gradients. The conclusion is that the placement of the ash lagoon has lead to significant changes in the hydraulics of the groundwater regime within the overburden, however, the degree of impact tends to vary across the site. Seepage velocities through the overburden have increased as a function of the hydraulic gradients, but a knowledge of groundwater velocities alone is insufficient for predicting travel distances of fly ash leachate constituents. The results of the geochemical testing of groundwater samples may provide direct evidence on the extent of contaminant migration. These results are provided in a separate report.

job	file	date	report no.
43-304-033	843.12	August 21, 1989	89-185-K

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GROUNDWATER STUDY AT NANTICOKE ASH LAGOON
PART 1: PHYSICAL HYDROGEOLOGY

1.0 INTRODUCTION

Ontario Hydro will be installing a flue gas desulphurization (FGD) system at the Nanticoke Thermal Generating Station (TGS) in the near future. The objective of this system will be to reduce acid gas emissions produced during the burning of coal at the station. The exact nature of the FGD waste material is unknown at this time, however, it can be assumed that it will consist primarily of gypsum and minor amounts of fly ash. The waste disposal method may consist of stacking the waste gypsum above ground on existing station property or adjacent properties.

To assess the impact of the proposed FGD waste disposal system on the local groundwater resources, a hydrogeological investigation, in the vicinity of the existing Nanticoke TGS fly ash disposal area, was initiated in the fall of 1986. Since the ash lagoon began operations in the early 1970's, any potential environmental impact should have already developed. This long-term investigation, conducted by the Soil Sciences Section of the Civil Research Department, would help clarify the extent of movement of ash leachate constituents from the disposal lagoon into the underlying clay overburden and bedrock. Assuming that the characteristics of fly ash leachate and FGD leachate are reasonably similar, the results of this study will assist in the siting of future FGD disposal systems.

The field program consisted of installing several nests of piezometers, both underneath and around the fly ash disposal lagoon, for the purposes of measuring hydraulic heads, hydraulic conductivities and obtaining water samples for chemical analyses. Soil sampling from underneath the ash lagoon was also undertaken to allow for chemical analysis of pore waters as well as trace element analysis of the soil itself.

This report provides the results of all of the hydraulic testing completed to date and the results of the on-going hydraulic head monitoring in the piezometer nests. The results of the geochemical investigation will be reported separately under Part 2.

1.1 Operating History of the Ash Lagoon

The Nanticoke Thermal Generating Station has a capacity of 4100 megawatts (MW) from its eight units and is one of the largest coal-fired stations in the world.

Construction began at the site in 1968 and all eight units were completed by late 1978. Simultaneous operation of all eight units began in 1981. A blend of US coal and low sulphur Canadian coal has been burned at the station since 1979 as one of the measures for controlling sulphur dioxide emissions. At full load, the plant will burn up to 1480 megagrams of coal per hour. Actual coal consumption and fly ash production varies with power demand, maintenance schedules at the plant and availability of electrical power from other sources within the Ontario Hydro grid. The average annual ash production at Nanticoke is approximately 600 Gg.

To handle the large quantities of fly ash and bottom ash produced during the coal burning process, a large above-ground lagoon was constructed with a surface area of 76 ha and a height of 12 m. The original ground surface was graded to an elevation of 184.75 m.ASL and a clay dyke was constructed up to an elevation of 197 m.ASL to form the lagoon. Levelling of the original ground surface required removal of up to 3 m of clay overburden throughout most of the ash disposal area. A natural drainage creek, flowing towards the southeast across the site, had to be filled in since its depth ranged from 1.2 m to 4.9 m below the design bottom of the lagoon/1/.

The ash handling operation, which began in 1972, consisted entirely of a wet system. The fly ash and bottom ash were sluiced from the station up to the lagoon and allowed to settle. The water within the reservoir was recirculated back to the station for ash transport. The lagoon also received aqueous waste from coal pile runoff, air preheater washes, demineralization plant, boiler cleaning and the sewage lagoon/2/. As the ash delta continued to build up over the years, the water level in the lagoon also began to rise such that in 1981, the exposed ash delta surface was approximately at elevation 195 m and the lagoon level was at elevation 194 m/3/. This translates to a hydraulic pressure of approximately 9 m of water acting at the top of the clay overburden.

In 1979, the Nanticoke station began blending low sulphur, Western Canadian coal with the Eastern US coal. The procedure had a detrimental effect on the recirculatory ash sluice system and the ash lagoon. The higher calcium oxide content of the Western Canadian coal increased the lagoon pH and also caused scaling problems within the sluicing system. The higher ash content of the Canadian coal contributed to reducing the expected operating life of the lagoon. Because of these and other factors, in 1981, the ash handling system was converted to a once-through wet ash transport system.

The new system, which is still in operation, involves sluicing the ash into several sedimentation cells. These cells were constructed by excavating into the existing ash delta and by constructing retaining dykes with compacted ash. Interconnection between the various cells is achieved through a series of culverts. The cells are periodically dredged and the accumulated ash stockpiled behind a berm to reduce wind erosion. The transport water is

clarified in a series of sedimentation cells and then further clarified in the primary lagoon before being circulated back to the station and discharged to the condenser cooling water outfall (Figure 1). The water level in the primary lagoon, which now only covers approximately one third of the original surface area, tends to fluctuate between elevations 189 m and 191 m, depending on coal consumption rates. The design height of the ash stockpile is at elevation 212 m or 15 m above the crest of the original clay dyke.

2.0 SITE GEOLOGY

The Nanticoke TGS is located in the physiographic region of southwestern Ontario known as the Haldimand Clay Plain. The overburden in the area consists mostly of a faintly layered, over-consolidated glacial-lacustrine clay which was deposited in glacial Lake Warren. The lacustrine clay is extensively fractured near the surface and the fracture frequency diminishes with depth.

Trench fracture mapping results reported by Golder Associates/4/ indicate that the majority of fractures are vertical to sub-vertical and are identifiable by a distinct blue-grey colouration along the fracture planes, as well as the presence of extensive root systems. Abundant horizontal to sub-horizontal partings were noted in association with thin silt layers suggesting the presence of varves. A third set of shallow dipping fractures (approximately 45^{0}) was also identified which had occasional slickenslided surfaces indicating previous movement in the direction of the dip. Fracture surfaces were visible at the base of the mapping trenches, which indicates that fracturing extends from the surface to a depth of at least 5.2 m below ground surface.

The detailed stratigraphy of the site consists of 8 to 11 m of lacustrine silty clay overlying 0 to 2 m of sandy silt till. The till is underlain by bedrock described as brownish-grey, fine-grained cherty limestone and known as the Dundee formation of Devonian age. The bedrock surface is occasionally highly fractured with fracturing decreasing with depth/4/.

In the vicinity of the Nanticoke ash lagoon, the bedrock surface elevation ranges from 175 to 177.5 m.ASL. Since the design bottom of the lagoon is at approximately elevation 185 m, this implies that overburden thickness underneath the lagoon varies from 7.5 to 10 m. With up to 3 m of overburden removed to obtain the design elevation of the lagoon, a large portion of the near-surface fractured zone was also removed and reworking of the clay surface may have sealed any remaining fractures. No specifications for the infilling of the creek which crosses the site, have been found. The effectiveness of this filling material, in terms of preventing preferential flow of fly ash leachate, is also unknown.

3.0 FIELD TESTING AND MONITORING

3.1 Piezometer Installation

All standpipe-type piezometers were constructed of 3.8 cm, inside diameter PVC pipe, slotted along a 30 to 120 cm length at one end and wrapped with geotextile. Most of the boreholes were drilled using 6-inch (15.2 cm) diameter hollow-stem augers and centrebit. Continuous or discrete soil sampling, using 4.7 cm diameter Shelby tubes, was performed during the installation of most piezometers. Piezometers were installed just below the till/bedrock contact by drilling a 1.5 m long core of the fractured limestone. Coarse filter material consisted of a mixture of pea gravel and/or sand and a 30 to 60 cm long bentonite plug was placed to seal the piezometer intakes. Piezometers installed outside of the ash lagoon were backfilled with native clay, while those inside the lagoon were backfilled to the near-surface with a cement/bentonite mix. Actual piezometer intake lengths are reported in a later section but, in general they range from 40 cm to 200 cm depending on location.

Piezometers were installed at six different locations in and around the fly ash lagoon, as shown in Figure 1. At each location, several piezometers were placed at different depths forming "nests" of monitoring points. The elevations of all monitoring points are given in Table I.

Nests #1 and #6 are located outside the southeast and northeast corners of the lagoon respectively. Nests #2 through #5 are located within the ash lagoon itself. At locations #2 and #3, two piezometers were placed in the ash, three in the overburden and one in the bedrock. At locations #4 and #5, two bundle piezometers were placed in the ash, five standpipe-type piezometers in the overburden and one in bedrock. The bundle piezometers consist of 0.9 cm and 1.3 cm diameter polyethylene tubing cut to specific lengths and bundled together. Each bundle consists of six tubes and each tube has a filtered intake up to 15 cm in length placed at one end. Monitoring points in the fly ash extend from 6 ft (1.8 m) to 28 ft (8.5 m) at 2 ft (0.6 m) intervals.

The six piezometer nests, shown in Figure 1, were installed at different times throughout the project. Nests #1 to #3 were installed in early-October of 1986. Nest #1 was used to provide background values of hydraulic heads and geochemistry. Nest #2 was installed to allow monitoring of hydrogeological parameters within the infilled drainage creek. Nest #3 was located in the area of the ash outlet pipes, to help determine the effects of long-term contact between the ash and overburden. Nests #4 and #6 were installed in April of 1987. Nest #4, similar to Nest #3, was used to provide hydraulic and geochemical data from the area of longest contact between ash and clay. Nest #6 was used to provide background data upgradient of the ash lagoon. Nest #5, installed in late-August, 1987, was used to provide additional data from underneath the ash lagoon and its location was chosen for purely practical reasons.

3.2 Field Hydraulic Conductivity Tests

Rising head hydraulic conductivity tests were conducted in most of the piezometers installed during this study. The objectives for conducting these tests were to 1) obtain a profile of hydraulic conductivity with depth through the overburden and bedrock, 2) determine if there are any hydraulic conductivity contrasts between the clay underneath the ash lagoon and the surrounding overburden, 3) provide necessary values for future estimates of groundwater velocity.

Since the slotted standpipes were installed in augered boreholes, there is a possibility that some remoulding or smearing may have occurred along the borehole walls. Any fractures intersected by the borings may have become plugged, thus reducing the apparent hydraulic conductivity of the test section.

After the installation of the piezometers, the water levels were allowed to equilibrate to static levels which were subsequently used in the rising head test analyses. The equilibration times varied from a few weeks to a couple of months depending on the formation permeability. The rising head tests were performed by bailing the piezometers down to near the intakes in preparation for future geochemical sampling. The recovery of the water levels was periodically measured using a standard water level meter and the analyses were performed using Hvorslev's method/5/. The Hvorslev plots associated with each test are provided in the Appendix. The hydraulic conductivity test results are tabulated in Table II along with data on the individual piezometer installations.

The results reported in Table II represent hydraulic conductivities within an influence zone around the piezometer tips. The size of this influence zone may vary from 1 to 5 borehole radii away from the centre of the piezometer tip. The volume of soil affected by the pore pressure equalization process is entirely dependent on the soil properties within the zone of influence (coefficient of permeability and consolidation) and the flexibility of the piezometer system/6/.

The importance of the above statements, with respect to the response tests conducted during this study, is that the results of Table II represent local hydraulic conductivities only. The values may be influenced by the presence of local soil fracturing which may not be regular enough to influence all test sections equally.

The hydraulic conductivities from the bedrock piezometers range from 2.6×10^{-5} cm/s to 4.3×10^{-4} cm/s with a geometric mean of 1.0×10^{-4} cm/s. These values are representative of the near surface bedrock (top 1.5 m) which has generally a low degree of fracturing, varying laterally as well as with depth. Solid core recoveries range from 65 to 100 per cent, as reported by Golder/4/, with localized fractured zones occurring at depths of 1.4 to 1.6 m below the bedrock surface in selected borings. Results of pressure packer tests reported by Golder indicate that hydraulic conductivities for the upper fractured bedrock range from 1×10^{-4} to 5×10^{-4} cm/s. Values for the lower bedrock are less than 1×10^{-6} cm/s which is the lower testing limit of the packer assembly.

The hydraulic conductivities for the ash piezometers range from 4.0×10^{-4} cm/s to 6.8×10^{-5} cm/s with a geometric mean of 1.3×10^{-4} cm/s.

Up to 3 metres of overburden was removed to obtain the design elevation of the lagoon bottom. The response tests performed in the piezometers of the remaining upper clay, resulted in K-values from 3.5×10^{-6} cm/s to 1.2×10^{-8} cm/s with a geometric mean of 2.4×10^{-7} cm/s. Piezometers in the lower clay (greater than 6 m below original ground surface) yielded K-values ranging from 9.1×10^{-7} cm/s to 1.0×10^{-8} cm/s with a geometric mean of 5.4×10^{-8} cm/s. Response tests in the lower till unit yielded K-values with a geometric mean of 2.5×10^{-7} cm/s.

Piezometer nests #1 and #6 are located outside of the ash lagoon area and therefore represent background conditions. Hydraulic conductivity test results from these nests are summarized by the following geometric means: 1) for the clay overburden, $K = 4.8 \times 10^{-8}$ cm/s, 2) for the till unit, $K = 6.8 \times 10^{-7}$ cm/s. There is no apparent permeability contrast within the clay overburden, as would be expected if the boreholes intersected any fractures. Based on test results reported by Golder/4/, who performed a total of 26 response tests in the overburden surrounding the lagoon area, there is a definite permeability contrast between the upper and lower clay zones. Different hydraulic conductivity magnitudes were obtained between two reference sites examined by Golder and Associates. The following geometric means summarize the test results: 1) for reference site 1 (west of lagoon), K (upper clay) = 3.1×10^{-6} cm/s and K (lower clay) = 1.1×10^{-7} cm/s; 2) for reference site 2 (east of lagoon), K (upper clay) = 1×10^{-7} cm/s and K (lower clay) = 4×10^{-8} cm/s. The differences between these two sites accentuates the heterogeneity in degree of fracturing across the deposit and underlines the difficulty in obtaining representative values of background conditions.

Depending on which set of background values are used for comparing with results from underneath the ash lagoon, two different conclusions can be drawn. Based on K-values from reference site 1, a reduction in hydraulic conductivity has taken place beneath the ash lagoon. This may be attributed to consolidation of the underlying clay by the increased vertical stress of the ash pile. Compared to the results of preference site 2, no significant change in hydraulic conductivity of the clay has taken place. An investigation into the consolidation characteristics and preconsolidation pressures of the underlying clay would help determine if enough vertical stress has been applied to the overburden to cause significant settlement and permeability reduction.

3.3 Long-Term Monitoring of Water Levels

Long-term monitoring of water levels within the six piezometer nests was undertaken for the following purposes: i) to determine equilibrium hydraulic head conditions necessary for hydraulic conductivity calculations and hydraulic gradient determinations, ii) monitor fluctuations in hydraulic head due to specific activities within the fly ash lagoon and iii) observe changes in hydraulic head due to seasonal changes in precipitation/evapotranspiration. Each nest of piezometers (#1 through #6) will be discussed separately in the following subsections.

3.3.1 Nest #1

Piezometer nest #1 is located approximately 70 m east of the southeast corner of the ash lagoon dyke. The nest consists of four piezometers with intakes placed at different depths, as given in Table I. Three piezometers are located in the clay overburden and one in bedrock. The intent of this piezometer nest was to provide background values on hydraulic gradient and geochemical conditions.

Water level data recorded at nest #1 is plotted in Figure 2. Fluctuations in water levels are due to hydraulic conductivity testing, bailing and water sampling activities which have taken place throughout the monitoring period. Based on equilibrium water level conditions, the vertical hydraulic gradient within the overburden varies from 0.04 to 0.08 downwards. The hydraulic head in the bedrock piezometer (#1-1) is substantially above the heads recorded in the overburden piezometers. This indicates that groundwater flow is occurring from the bedrock towards the overburden with a vertical hydraulic gradient ranging from 0.15 to 0.2.

The hydraulic head within the overburden fluctuates around 181 m.ASL which is similar to background conditions from an adjacent site as reported by Golders/4/. The head values in the shallow bedrock fluctuated around 181.6 m.ASL which is approximately 6 metres above background conditions as reported by Golders/4/. This discrepancy is probably because piezometer #1-1 is located in the shallow bedrock horizon which is influenced by an overlying higher permeability sandy till unit. The Golder's values are more representative of hydraulic heads in the deeper bedrock.

3.3.2 Nest #2

Piezometer nest #2 is located along one of the finger roads in the eastern half of the ash storage area (see Figure 1). This nest is comprised of six piezometers: 2-6 and 2-5 were placed in the fly ash at depths of 3 and 6 metres respectively; 2-4, 2-3 and 2-2 were placed in the overburden at depths of 9, 10.7 and 13.7 m below the ash surface; 2-1 was keyed into the bedrock at a depth of 16.8 m below the ash surface. The elevations of these piezometers are given in Table I. Nest #2 was placed such as to intersect an old creek bed which cut across the ash lagoon area from west to east. The creek was backfilled with native soil to obtain a uniform bottom elevation of 184.75 m.ASL during the construction of the lagoon.

The water level data recorded for Nest #2 is presented in Figure 3. Piezometers 2-5 and 2-6 indicate the water pressure within the ash underneath the finger roads. Throughout most of the monitoring period, the water level was above the level of fly ash. The similarity in water levels between these two piezometers indicates that there is no vertical flow of ash porewater at this location.

Overburden piezometers 2-2, 2-3 and 2-4 indicate that total heads within the overburden are approximately 186 m, 191 m and 192 m.ASL respectively. Compared to a background value of 181 m.ASL measured at Nest #1, excess hydraulic head has developed within the overburden due to the presence of the ash lagoon.

A non-linear hydraulic gradient has developed through the 8.5 metres of overburden. The vertical hydraulic gradient (i_v) between piezometers 2-4 and 2-3, which are 1.8 m apart, is equal to 0.5. Between 2-3 and 2-2, which are 3 m apart, i_v = 1.7. These values are based on water level readings taken January 5, 1989. These gradients have remained relatively constant throughout the monitoring period as shown by the water level data of Figure 3.

The total head recorded in bedrock piezometer 2-1 is higher than the head recorded in the deepest overburden piezometer 2-2. This indicates that an upward flow of groundwater with a hydraulic gradient of 0.2 exists between the shallow bedrock and overlying till. This same phenomenon has been observed at Nest #1.

3.3.3 Nest #3

Piezometer Nest #3 was located just to the east of the fly ash outlet pipe as shown in Figure 1. The intent of this nest location was to determine and monitor the geochemistry of natural groundwater below the oldest part of the ash lagoon. The nest was comprised of six piezometers: 3-6 and 3-5 were placed at depths of 3.3 m and 7.6 m into the fly ash respectively; 3-4, 3-3 and 3-2 were placed in the overburden at depths of 12.2 m, 15.2 m and 18.3 m below the top of the ash; 3-1 was keyed into the bedrock at a depth of 20.7 m below the top of the ash. The fly ash/overburden interface at Nest #3 is located between 11.6 and 12.2 metres below the top of the ash.

The water level data recorded at Nest #3 is plotted in Figure 4. The water levels were not significantly influenced by rising head permeability tests (April/87) and water sampling activities (Jan/87, June/87, July/88). This is an indication of the relatively high hydraulic conductivity of the soil in the vicinity of the piezometer intakes (see Table II). The fluctuations noted in all the water level data are most likely caused by changes in the local water table within the ash, which is itself influenced by seasonal precipitation as well as the amount of water percolating through the nearby ash settling cells.

The similarity in total levels between fly ash piezometers 3-6 and 3-5 and overburden piezometers 3-4 and 3-3 indicates that there is little head loss between the ash lagoon and the underlying clay down to a minimum depth of 15.2 m below the top of the ash, ie approximately 3 metres below the ash/clay interface. Whether this good interconnection is through fractures in the clay or through poorly backfilled boreholes is unknown. Assuming that the total heads are influenced by natural causes, excess heads of between 10 to 14 m above background (181 m.ASL) have developed underneath the ash lagoon.

A hydraulic gradient of 0.03 exists between piezometers 3-4 and 3-3, representing the top 3.2 m of overburden. Through the subsequent 3 m, between 3-3 and 3-2, an i_v of 1.4 has developed. This dramatic non-linearity in hydraulic gradient may be an indication of the variability in hydraulic conductivity through the overburden thickness.

No useful data has been collected from bedrock piezometer 3-1 since it apparently developed some leakage problems shortly after installation. Following the second water sampling period in June/87, this piezometer was completely backfilled and abandoned.

Piezometer Nest #3 was completely backfilled and abandoned in January/89 to make room for additional dust control activities within the ash storage area.

3.3.4 Nest #4

Piezometer Nest #4 is located on the west edge of the bottom ash cell as shown in Figure 1 and consists of 6 standpipe piezometers and 2 bundle piezometers. Each bundle piezometer is made of 3/8 inch (0.95 cm) tubing cut to varying lengths such that intakes are spaced every 2 feet (60 cm). The bundle piezometers were placed exclusively within the fly ash from a depth of 4 ft (1.2 m) to 28 ft (8.5 m). The bottom of the ash lagoon at this location is between 8 to 9.2 m below the top of the ash. The elevations of the standpipe piezometers are given in Table I. Piezometers 4-2 to 4-6 are placed within the overburden at depths of 18.5, 17, 15.4, 13.6 and 12 m respectively below the top of the ash. Piezometer 4-1 is keyed into the bedrock at a depth of 19 m below the top of the ash.

The water level data collected at Nest #4 is plotted in Figure 5. This nest was installed in late April/87 and monitoring began in May. Rising head tests (August/87), bailing (March/88) and sampling (July/88) have produced noticeable fluctuations in water levels for piezometers 4-2, 4-3 and 4-5. The hydraulic conductivities determined from these piezometers are all approximately 1×10^{-8} cm/s, as shown in Table II. The remaining piezometers have much higher K-values which would result in faster recovery rates.

The most striking feature of Figure 5 is that piezometer 4-4, located deeper than either 4-6 and 4-5, exhibits a total head which is higher than those recorded in 4-6 and 4-5. This phenomenon can only take place if the intake of piezometer 4-4 is somehow interconnected to a source of higher head such as the water table within the lagooned fly ash. Two scenarios are possible: 1) the intake is connected via extensive vertical fractures to the bottom of the ash lagoon, 2) the bentonite seal and grout backfill have failed allowing preferential flow through the borehole annulus. It is almost impossible to determine which scenario is the most likely, however, examination of geochemical data may provide some answers.

Based on water level data obtained on January 5, 1989, and ignoring the data from piezometer 4-4, the following hydraulic gradients have developed through the overburden below Nest #4: i) $i_v = 0.56$ between 4-6 and 4-5, ii) $i_v = 0.91$ between 4-3 and 4-2 and iii) $i_v = 0.86$ between 4-2 and 4-1. The changing hydraulic gradients through the overburden serve as an indication of heterogeneous hydraulic conductivity conditions.

Excess heads of 8 to 13 m above background have developed within the overburden. Within the bedrock an excess head of 8 m has also developed when compared to background conditions at Nest #1. The validity of this pressure within the bedrock may be questioned in view of the fact that the hydraulic conductivity for this section is 2.6×10^{-5} cm/s or three orders of magnitude greater than the overburden hydraulic conductivity. The shallow bedrock horizon is fractured and quite permeable. However, the degree of fracture interconnection may not be extensive enough to allow quick dissipation of excess hydraulic pressures.

Monitoring of water levels within the fly ash bundles has also taken place. These water levels indicate that a vertical flow system under a hydraulic gradient of 0.1 to 0.2, has developed in the top 6 m (20 ft) of fly ash. This flow system is evidence of water percolating downwards from the settling cells to about 6 m and then flowing away horizontally. Stagnant flow conditions exist below 6 m as evidenced by the similar total head values recorded in the deeper bundle.

3.3.5 Nest #5

Piezometer Nest #5 is located on the southwest corner of a slag-covered area north of the ash settling cells shown in Figure 1. The nest consists of six standpipe piezometers and two bundle piezometers. The bundle piezometers are constructed of 1/2 inch (1.3 cm) tubing and are placed solely within fly ash at 2-foot (60 cm) intervals similar to Nest #4. Five of the six standpipes are located in the overburden, with the uppermost piezometer, 5-6, located just 30 cm below the fly ash/clay interface. The elevations of all piezometer tips are given in Table I.

Nest #5 was installed at Nanticoke in late August/87 and water level monitoring began in Sept/87. All of the water level data are plotted in Figure 6. The influence of rising head tests (May/88) bailing and sampling (July/88) can be observed in the response of the less permeable (1.5×10^{-8} cm/s) piezometers 5-3 and 5-4. Fluctuations in water levels for piezometers 5-5 and 5-6 can be directly correlated to filling and draining of the northern-most ash settling cell. This implies good interconnectivity below the ash lagoon and the top 2 m of overburden.

A vertical hydraulic gradient of 0.2 has developed between piezometers 5-6 and 5-2 representing an overburden thickness of 5.7 metres. A steep hydraulic gradient of 1.6 has developed between the deep overburden and shallow bedrock. Excess hydraulic heads of 11 to 12 m above background have developed within the overburden and an excess head of 7 m has developed with the shallow bedrock when compared to background values at Nest #1.

Water level monitoring in the fly ash bundle piezometers was also conducted. The total heads within the fly ash were similar through the entire profile indicating that very little vertical flow of water occurs at this location in the ash lagoon. The water levels measured in bundles are very similar in magnitude to those measured in overburden piezometers 5-6 and 5-5.

3.3.6 Nest #6

Piezometer Nest #6 consists of a series of seven piezometers placed at different depths for measuring vertical gradients and of three piezometers placed in a triangular configuration for measurement of horizontal gradients. The piezometers are located in the northeast corner of the station property, approximately 25 m north of the toe of the outside berm. Table I provides the elevations of the piezometer intakes for Nest #6.

The piezometers used for measuring the horizontal hydraulic gradient are placed in the configuration of a triangle with 6.1 m long sides and approximately 60^0 internal angles. The three piezometer intakes were all placed at a depth of 6.1 m below ground surface or at an elevation of 183.4 m.ASL. Based on water levels recorded on November 5, 1987, the horizontal hydraulic gradient equals 0.1 at 3 degrees azimuth. This value is substantially different from background values recorded by Golder Associates/4/ which gave a horizontal gradient of approximately 0.005 to the southeast towards Lake Erie. The only explanation for this result is that the water level within the ash lagoon is influencing local groundwater levels to such an extent that flow directions have reversed. In Figure 7, which is a plot of water levels from the triangular piezometer nest, the difference between the piezometers has remained fairly constant indicating that the magnitude and direction of the horizontal gradient has also remained constant. The exception is during the month of June/88 when the water levels were recovering from bailing of the piezometers in mid-March. During this period of time, hydraulic head values from piezometers 6-T1 and 6-T3 were similar. Based on their configuration, this indicates that the direction of flow had changed to 30^0 azimuth and the magnitude had remained at approximately 0.1.

Piezometers 6-1 to 6-7 were placed at different depths within the overburden to measure vertical hydraulic gradients and hydraulic conductivities. The elevation of the piezometer intakes are given in Table I and the intake lengths of the piezometers are all approximately 45 to 50 cm.

Figure 8a represents water level elevation changes with time for piezometers 6-1, 6-2 and 6-3 which are located in the bedrock and overlying till respectively. The water levels in these three piezometers have been very consistent through time, with only minor fluctuations occurring within the till in winter/87 and fall/88. Based on these water levels, there is no significant flow between the till and shallow bedrock. In fact, these two zones appear to be acting as one hydraulic unit with a minimum thickness of 1.3 m. The hydraulic head within this zone is at approximately 188 m.ASL.

Figure 8b represents water level changes with time in the shallower piezometers 6-4, 6-5, 6-6 and 6-7. These piezometers are all located in relatively lower permeability soils, and therefore recovery times are much longer following testing and sampling. Rising head hydraulic conductivity tests were performed in these piezometers in August/87 and the water levels were still recovering several months afterwards. One set of water samples was collected for analysis at the end of July/88 followed by a slow recovery of water levels throughout the fall. The recovery of water levels in piezometers 6-6 and 6-5 during late May/early June is due to bailing of these piezometers in mid-March. The subsequent drop in water levels throughout late June/early July was probably caused by decreased precipitation and increased evapotranspiration during these months.

The magnitudes and directions of hydraulic gradients should be calculated when hydraulic heads have reached equilibrium conditions. By examining Figure 8b, it is difficult to choose a time period for gradient calculations which represents a state of equilibrium. Therefore, the water level data recorded on January 5, 1989 have been used for hydraulic gradient calculations. The vertical gradient between 6-7 and 6-3 is equal to 0.1, which represents the

gradient through the top 7 m of overburden. This value coincides with gradients reported by Golders/4/. There appears to be no vertical groundwater flow within the bottom 1.3 m which is comprised of the till/bedrock interface. The unusually high water level in piezometer 6-4 has not been taken into account in the hydraulic gradient calculation since it would imply an upward flow of groundwater within a zone of overburden. The high water level in piezometer 6-4 (depth = 5.6 m.BGL) may represent hydraulic interconnection to the near surface via vertical fractures in the clay. This piezometer is also located at approximately the same depth as the triangular nest piezometers which indicates that significant horizontal flow is taking place at that elevation. This may also influence the hydraulic head being measured in 6-4.

3.4 Discussion

The construction and filling of the Nanticoke ash lagoon has lead to a significant increase in hydraulic head beneath the lagoon when compared to initial background conditions. This increase is a function of the height of water within the lagoon and is evidence of the new flow system created within the overburden. Figure 9 is a plot of total head with depth for each of the piezometer nests (#1 to #6). The water levels recorded on January 5th, 1989 have been used to determine the total heads associated with each piezometer. This plot clearly indicates the magnitude of excess heads imposed on the overburden beneath the lagoon (nests 2, 3, 4 and 5). The total heads associated with nests 1 and 6 represent background conditions within the clay overburden and bedrock. The difference in total head between these two nests allows calculation of the background horizontal gradient of groundwater flow which has a magnitude of 0.007.

The magnitude of excess hydraulic heads beneath the ash lagoon vary from location to location. The actual magnitudes are partially dependent upon the height of water within the ash above the overburden. At nests #3 and #4, the water levels in the ash are higher due to the presence of the ash settling cells and the associated percolation of water from them. Correspondingly, the total heads are higher within the underlying clay and represent excess heads between 6 and 13.5 metres above background conditions. At nests #2 and #5, the excess heads vary from 2.5 to 8.5 metres within the overburden since the height of water above the ash/clay interface is less. Figure 9 confirms that hydraulic conditions across the site are not homogeneous.

The excess heads measured in the bedrock piezometers are between 3 and 6 metres above background conditions depending on location. These surprisingly high values and the equally high values measured in the overburden may be explained by the fact that the fractured bedrock drainage boundary is relatively thin compared to the height of the ash lagoon itself. The water within the 76 ha lagoon is draining through the clay/till overburden towards the fractured bedrock zone which is hydraulically connected to the lake. Even though the shallow bedrock zone has a relatively high hydraulic conductivity (10^{-4} to 10^{-5} cm/s)/4/, it is apparently not thick enough to permit quick drainage of water flowing from the overburden. This phenomenon, plus the proximity of the constant head boundary represented by the lake, has lead to the generation of high hydraulic heads within the shallow overburden.

The non-linear hydraulic gradients developed under the ash lagoon and shown in Figure 9, are representative of the vertical heterogeneity in hydraulic conductivity within the clay overburden. Groundwater flowing through a high permeability medium will experience less head loss because of the reduced resistance to flow. Conversely, the same amount of groundwater flow will experience more head loss through lower permeability materials. This is represented in Figure 9 by the head loss profiles of nests #2, 3, 4 and 5. In general, there is less head loss, through the shallow clay, more head loss through the deeper clay followed by less head loss in the more permeable till. The head profiles through the clay indicate that some secondary permeability, possibly fractures, exists within the shallow overburden.

Two anomalies exist in the above profiles. The relatively smaller head losses measured in Nest #5 indicate that most of the overburden thickness is of a higher hydraulic conductivity. Based on rising head test results tabulated in Table II, there should be an approximate 1.5 order of magnitude reduction in hydraulic conductivity with depth. This apparent contradiction suggests that the hydraulic conductivities in the vicinity of the piezometer intakes have been reduced during augering of the borehole. The head loss profile determined in nest #4 is much more difficult to explain. The significant difference in total head between the deepest fly ash bundle and the first piezometer below the ash/clay interface, may indicate the presence of some low hydraulic conductivity materials near the interface. The higher hydraulic conductivity measured in 4-4 ($K = 2 \times 10^{-7}$ cm/s) is consistent with the fact that less head loss has been measured between the adjacent piezometers 4-5 and 4-3. As discussed in section 3.3.4, the higher total head measured in 4-4 may be evidence of local interconnection to the lagoon level via discrete vertical fractures.

In summary, the vertical hydraulic gradients through the overburden based on total heads within the ash lagoon and shallow bedrock are as follows: i_v for Nest #2 = 0.73, i_v for Nest #3 = 0.73, i_v for Nest #4 = 0.67 and i_v for nest #5 = 0.62. These gradients are in contrast with vertical gradients of 0.1 reported for the overburden in the vicinity of the ash lagoon/4/.

The height of water within the ash lagoon has also influenced local horizontal gradients as discussed in section 3.3.6 on Nest #6. Based on water level measurements from a triangular nest of piezometers, 6-T1 to 6-T3, the local horizontal hydraulic gradient equals 0.1 to the north. This is significantly different than the background gradient of 0.005 to the southeast. This triangular nest is located approximately 25 m north of the toe of the clay dyke and 6.1 m below ground surface. The extent of the zone of reversed groundwater flow is unknown at this time, however, it is likely that it extends across the entire north side of the ash lagoon.

4.0 CONCLUSIONS

The placement of the ash lagoon on top of the clay overburden at Nanticoke TGS has had a significant influence on the underlying groundwater regime. Most importantly, the hydraulic heads within the overburden and shallow bedrock have increased more than 10 m above background in some cases. The magnitude of these excess heads is dependent upon the height of water within the ash lagoon and on the inability of the shallow fractured bedrock zone to drain the

system effectively. The high excess heads generated within the shallow bedrock have also lead to smaller hydraulic gradients within the overburden than would have been generated in the case of a better drainage boundary.

The average hydraulic gradients, through the overburden beneath the lagoon, are between 0.6 and 0.7 downwards. These gradients are non-linear and vary depending on the heterogeneity of hydraulic conductivity through the overburden. The average gradients represent an increase of between one-half to three-quarters of an order of magnitude above background conditions. Assuming that material properties, such as hydraulic conductivity and porosity, have not changed significantly due to effective stress increases, groundwater seepage velocities will have changed by similar orders of magnitude. As discussed in Section 3.2, there is no conclusive evidence to suggest that overburden hydraulic conductivities have changed due to loading from the ash lagoon.

The hydraulic gradients and overburden hydraulic conductivities (geometric mean) used in seepage velocity calculations are as follows: i) for Nest #2, i_v = 0.73, K = 3.9 x 10^{-7} cm/s; ii) for Nest #3, i_v = 0.73, K = 2 x 10^{-6} cm/s; iii) for Nest #4, i_v = 0.67, K = 2.9 x 10^{-8} cm/s; iv) for Nest #5, i_v = 0.62, K = 7.2 x 10^{-8} cm/s. Based on an average clay porosity of 40% (calculated from initial void ratios for consolidation tests) an estimate of seepage velocities through the overburden can be obtained for each nest: i_v^2 = 22 cm/a; i_v^3 = 115 cm/a; i_v^4 = 1.5 cm/a; i_v^5 = 3.5 cm/a. Since the top 5 m of original clay overburden is fractured, the use of a fracture porosity value may be more appropriate for seepage velocity calculations. Fracture porosities can be several orders of magnitude less than matrix porosity/7/, which would significantly increase the magnitude of seepage velocities.

A knowledge of groundwater seepage velocities is insufficient to estimate total contaminant transport distances unless plug flow is assumed. In the case of the Nanticoke ash lagoon, one would have to assume that the above hydraulic gradients have remained constant throughout the 17-year operating life of the lagoon. This is unlikely, since the water level within the lagoon has fluctuated substantially during this time period, as a function of ash production.

The influence of molecular diffusion, mechanical dispersion and chemical retardation have been shown to be significant in the contaminant transport process/7/. All estimates of groundwater velocities obtained from Nest #2 to #5 are greater than 1 cm/a. This suggests that contaminant transport will be dominated by advective processes/8/, which then requires some knowledge of longitudinal and transverse dispersivities to estimate transport distances. Regardless of the mechanism involved, whether diffusion or dispersion, the tendency is for transport distances to be greater than those estimated for plug flow alone. In contrast to the above, the process of chemical retardation through adsorption, precipitation, ion pairing or complexation, etc, will act to reduce contaminant transport distances of specific ions, relative to plug flow distances. Some knowledge of distribution coefficients, between ions and soils of interest, is required to assess the effect of retardation. If contaminant transport occurs along fracture planes, and fracture flow velocities are low enough, molecular diffusion into the

surrounding matrix will also act as an additional retardation process. The importance of the above factors must be assessed before any estimate can be made of transport distances of fly ash leachate through the clay overburden.

The results of sampling and testing of groundwaters, from the overburden below the ash lagoon, should identify the extent of ash leachate migration. However, temporal and spatial variations in hydraulic parameters, such as hydraulic gradients and hydraulic conductivities, may have a significant influence on the consistency of the geochemical results. In addition, the effect of long-term leaching of the lagooned ash by percolating waters, may have been to cause temporal variations in the fly ash leachate geochemistry at the source. Since the magnitudes of these variations are presently unknown, any trends in groundwater geochemistry may prove difficult to interpret.

ACKNOWLEDGEMENTS

The cooperation and assistance of the staff at Nanticoke TGS, most notably Messrs T. Kokus and L. Steele, is gratefully acknowledged during the installation and monitoring of piezometers.

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TABLE I

NANTICOKE FLY ASH LAGOON PIEZOMETER ELEVATION

Piezometer No.		Ground Elevation (m ASL)	Top of Pipe Elevation (m ASL)	Piezometer Elevation (m ASL)
1-4		184.88	185.38	180.61
1-3		184.87	185.75	178.92
1-2		184.92	185.75	180.35
1-1		184.92	185.79	174.25
2-6	(fly ash)	192.55	193.45	189.50
2-5	(fly ash)	192.60	193.40	186.50
2-4		192.61	193.48	183.46
2-3		192.60	193.70	181.93
2-2		192.66	193.74	178.94
2-1		192.61	193.47	175.84
3-6	(fly ash)	197.95	198.56	194.59
3-5	(fly ash)	197.92	199.07	190.29
3-4		197.92	198.71	185.72
3-3		197.80	198.75	182.55
3-2		197.93	198.93	179.64
3-1		197.92	198.78	177.19
4-6		196.99	197.84	185.05
4-5		196.96	197.22	183.32
4-4		197.01	197.77	181.61
4-3		196.96	197.71	180.04
4-2		197.04	197.87	178.59
4-1		197.05	197.97	178.07
5-6		195.96	196.89	183.90
5-5		195.90	196.76	182.80
5-4		195.88	196.65	181.25
5-3		195.86	196.74	179.70
5-2		195.88	196.83	178.20
5-1		195.87	196.75	175.75
6-7		189.02	189.79	187.95
6-6		189.00	189.81	186.41
6-5		189.02	189.78	184.90
6-4		189.01	189.80	183.37
6-3		189.03	189.79	181.86
6-2		189.05	189.82	181.03
6-1		189.04	189.78	180.56
6-T1		189.07	189.88	183.43
6-T2		188.99	189.89	183.35
6-T3		189.13	189.83	183.49

TABLE II

Nanticoke GS Ash Lagoon
Field Hydraulic Conductivity Test Results (Rising Head)

PIEZO NO.	SOIL TYPE	PIPE/TIP DIA (cm)	DEPTH (m BGL)	SAND PACK L(cm)	K (cm/s)	PIPE r(cm)	HOLE R(cm)	TIME To(sec)	BENTONITE SEAL(cm)
1-4	CLAY	3.8 PVC	6.80	182.88	9.83E-08	1.90	7.62	3.19E+05	121.92
1-3	TILL	3.8 PVC	8.50	182.88	1.90E-07	1.90	7.62	1.65E+05	365.76
1-2	TILL	3.8 PVC	9.60	457.20	7.15E-07	1.90	7.62	2.26E+04	121.92
1-1	B/R	3.8 PVC	12.19	121.92	2.66E-04	1.90	3.78	1.93E+02	426.72
2-6	ASH	3.8 PVC	5.15	121.92	8.96E-05	1.90	7.62	4.58E+02	30.48
2-5	ASH	3.8 PVC	8.30	121.92	6.85E-05	1.90	7.62	5.99E+02	30.48
2-4	CLAY	3.8 PVC	10.95	91.44	5.93E-07	1.90	7.62	8.28E+04	30.48
2-3	CLAY	3.8 PVC	13.00	121.92	5.37E-08	1.90	7.62	7.65E+05	30.48
2-2	TILL	3.8 PVC	16.20	121.92	1.84E-06	1.90	7.62	2.23E+04	30.48
2-1	B/R	3.8 PVC	18.60	121.92	4.85E-05	1.90	3.78	1.06E+03	121.92
3-6	ASH	3.8 PVC	3.36	-	-	1.90	7.62	-	-
3-5	ASH	3.8 PVC	9.10	76.20	4.01E-04	1.90	7.62	1.36E+02	-
3-4	CLAY	3.8 PVC	14.00	121.92	3.51E-06	1.90	7.62	1.17E+04	30.48
3-3	CLAY	3.8 PVC	17.05	91.44	9.15E-07	1.90	7.62	5.36E+04	30.48
3-2	TILL	3.8 PVC	20.60	121.92	2.63E-06	1.90	7.62	1.56E+04	30.48
3-1	B/R	3.8 PVC	22.86	213.36	4.32E-04	1.90	3.78	7.90E+01	30.48
4-6	CLAY	3.8 PVC	11.94	101.60	4.00E-08	1.90	7.62	1.15E+06	203.20
4-5	CLAY	3.8 PVC	13.64	83.82	1.23E-08	1.90	7.62	4.21E+06	226.06
4-4	CLAY	3.8 PVC	15.40	76.20	2.07E-07	1.90	7.62	2.63E+05	30.48
4-3	CLAY	3.8 PVC	16.92	60.96	1.02E-08	1.90	7.62	6.03E+06	60.96
4-2	TILL	3.8 PVC	18.45	60.96	2.06E-08	1.90	7.62	2.99E+06	60.96
4-1	B/R	3.8 PVC	18.98	137.16	7.00E-05	1.90	3.78	6.75E+02	30.48
5-6	CLAY	3.8 PVC	12.65	60.96	4.77E-07	1.90	7.62	1.29E+05	30.48
5-5	CLAY	3.8 PVC	13.72	60.96	4.34E-07	1.90	7.62	1.42E+05	30.48
5-4	CLAY	3.8 PVC	15.24	60.96	1.72E-08	1.90	7.62	3.57E+06	30.48
5-3	CLAY	3.8 PVC	16.77	60.96	1.40E-08	1.90	7.62	4.41E+06	30.48
5-2	TILL	3.8 PVC	18.29	60.96	3.95E-08	1.90	7.62	1.56E+06	30.48
5-1	B/R	3.8 PVC	21.64	152.40	2.61E-05	1.90	3.78	1.68E+03	30.48
6-7	CLAY	3.8 PVC	1.07	45.72	-	1.90	7.62	-	61.00
6-6	CLAY	3.8 PVC	2.59	45.72	1.87E-08	1.90	7.62	3.78E+06	61.00
6-5	CLAY	3.8 PVC	4.12	45.72	2.05E-08	1.90	7.62	3.45E+06	30.48
6-4	CLAY	3.8 PVC	5.64	45.72	4.78E-08	1.90	7.62	1.48E+06	30.48
6-3	CLAY	3.8 PVC	7.17	45.72	8.23E-07	1.90	7.62	8.59E+04	30.48
6-2	TILL	3.8 PVC	8.02	67.06	5.42E-07	1.90	7.62	1.08E+05	61.00
6-1	B/R	3.8 PVC	8.47	173.74	9.94E-05	1.90	3.78	4.00E+02	30.48

○ PIEZOMETER NEST LOCATIONS

FIGURE 1
AERIAL PHOTO OF NANTICOKE TGS ASH LAGOON (1988)

89-185
180244-S18-RD

WATER LEVEL CHANGES AT NANTICOKE TGS

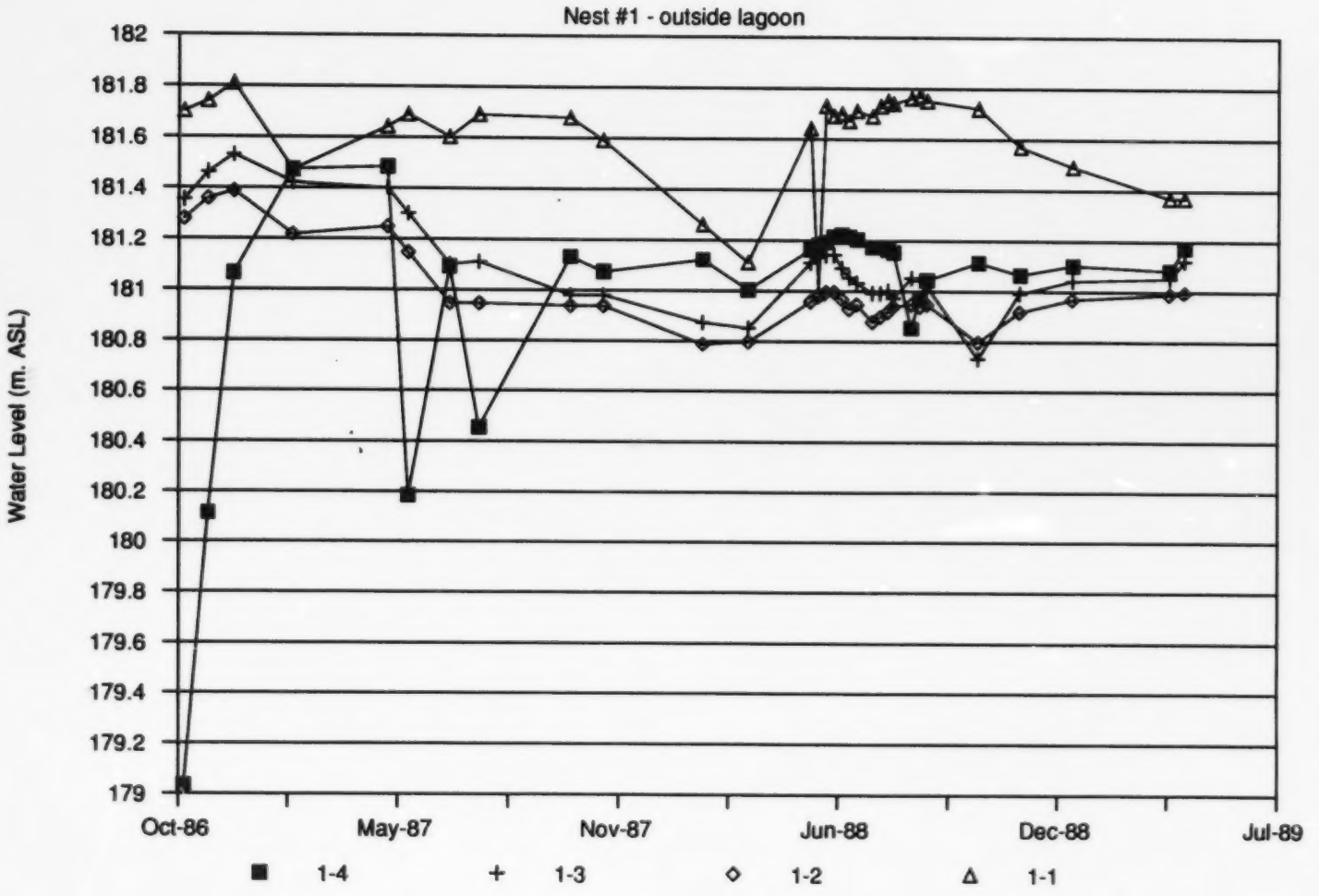

FIGURE 2

WATER LEVEL CHANGES AT NANTICOKE TGS

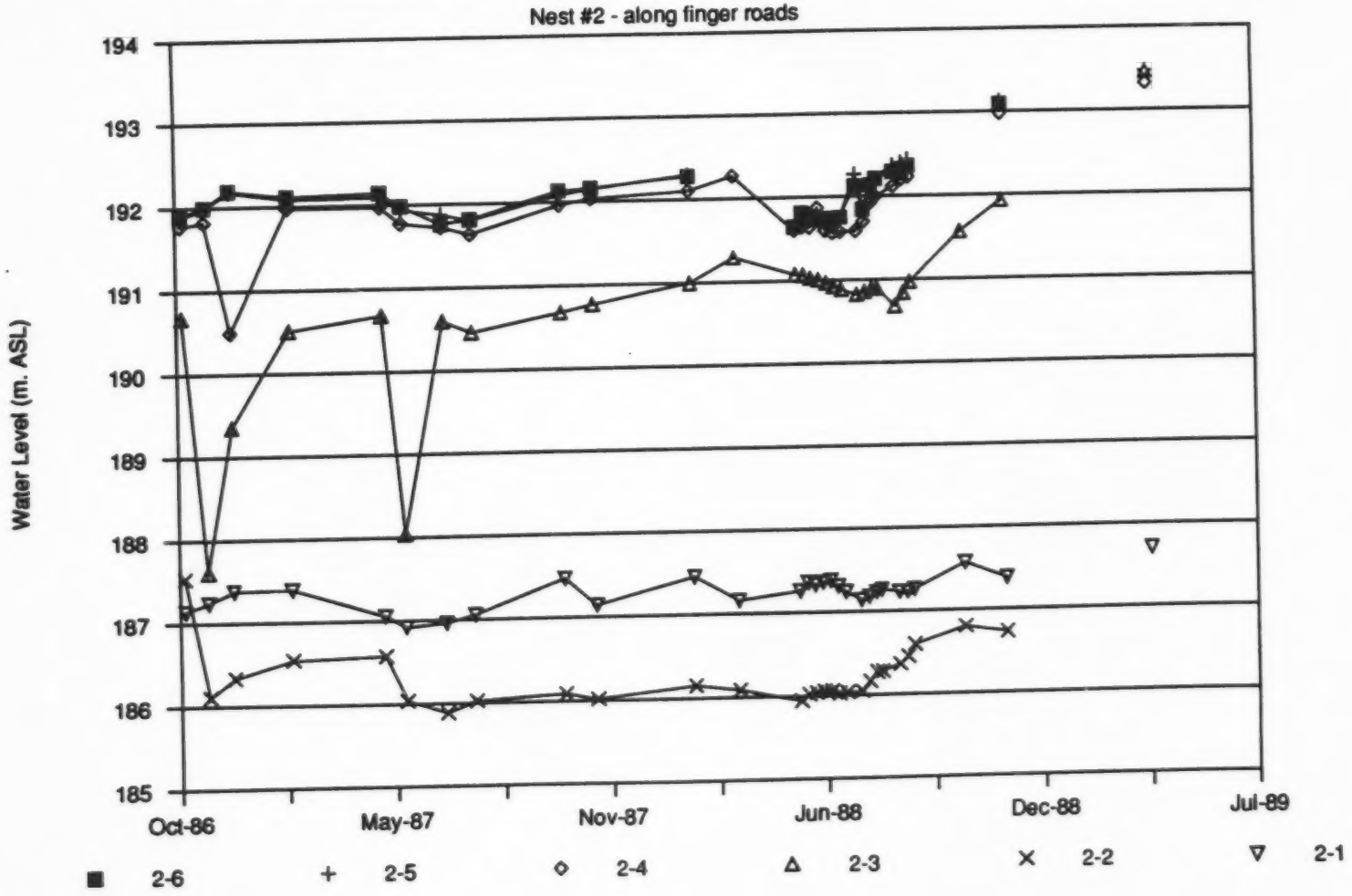

FIGURE 3

WATER LEVEL CHANGES AT NANTICOKE TGS

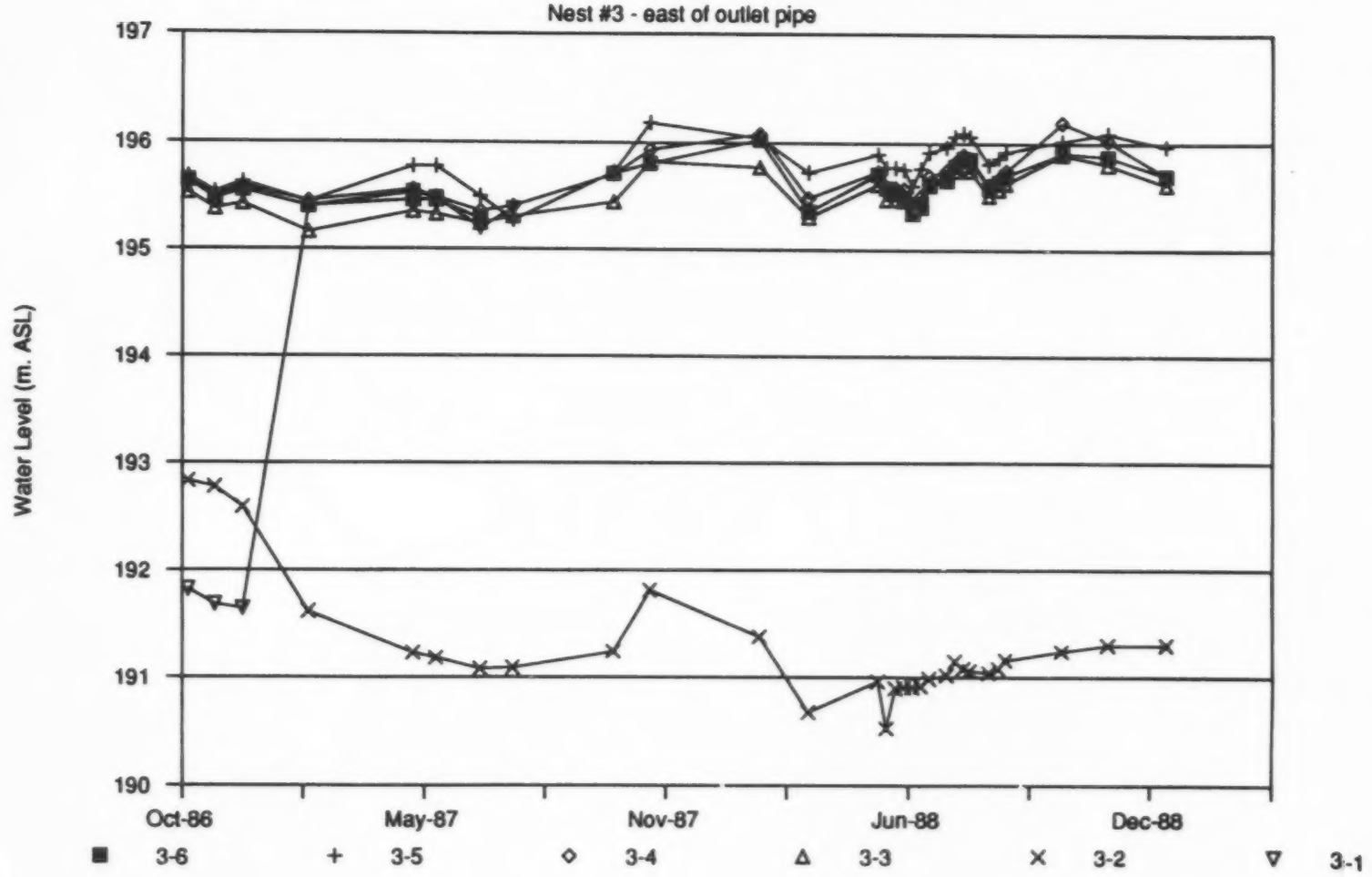

FIGURE 4

WATER LEVEL CHANGES AT NANTICOKE TGS

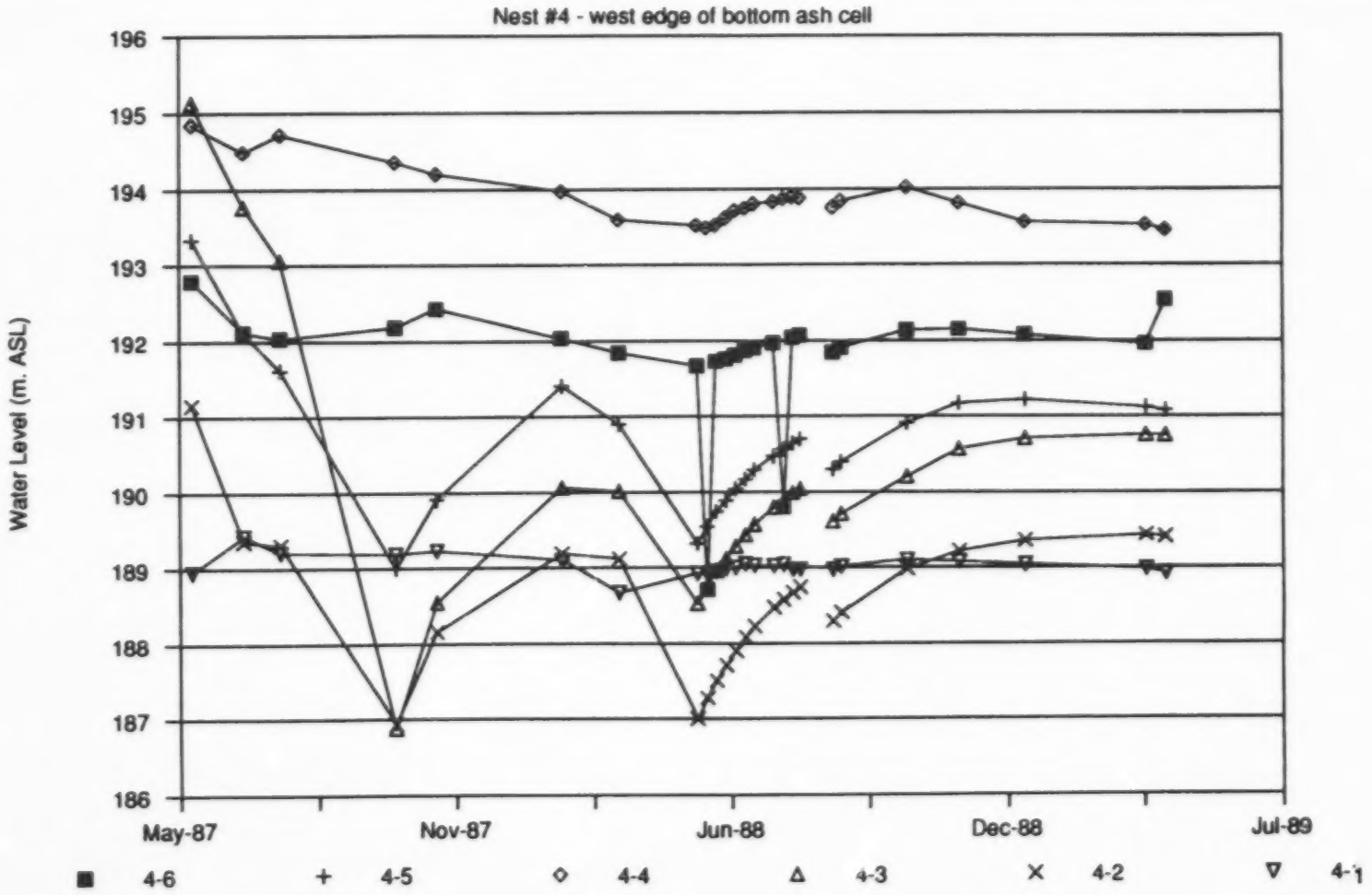

FIGURE 5

WATER LEVEL CHANGES AT NANTICOKE TGS

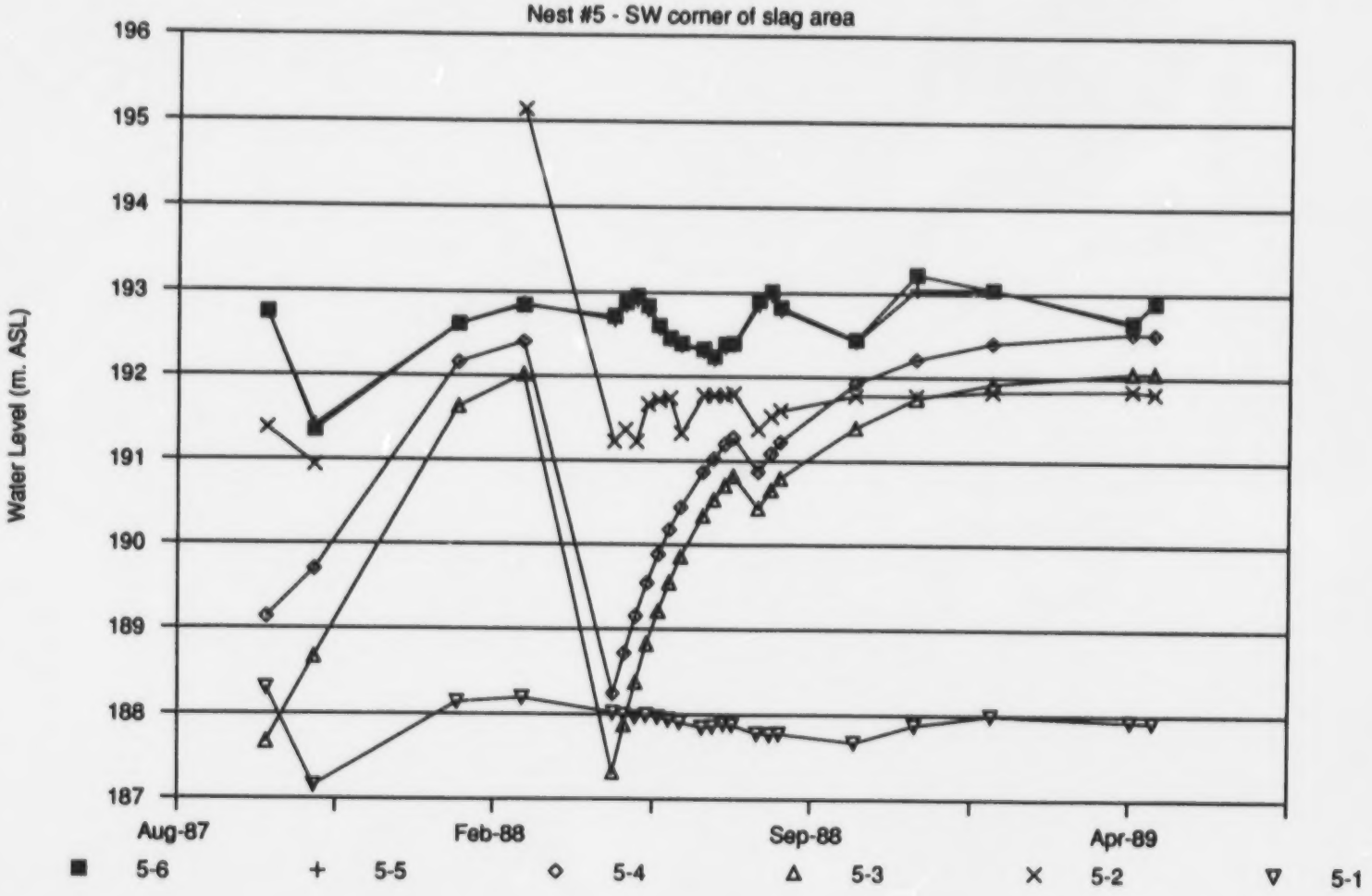

FIGURE 6

WATER LEVEL CHANGES AT NANTICOKE TGS

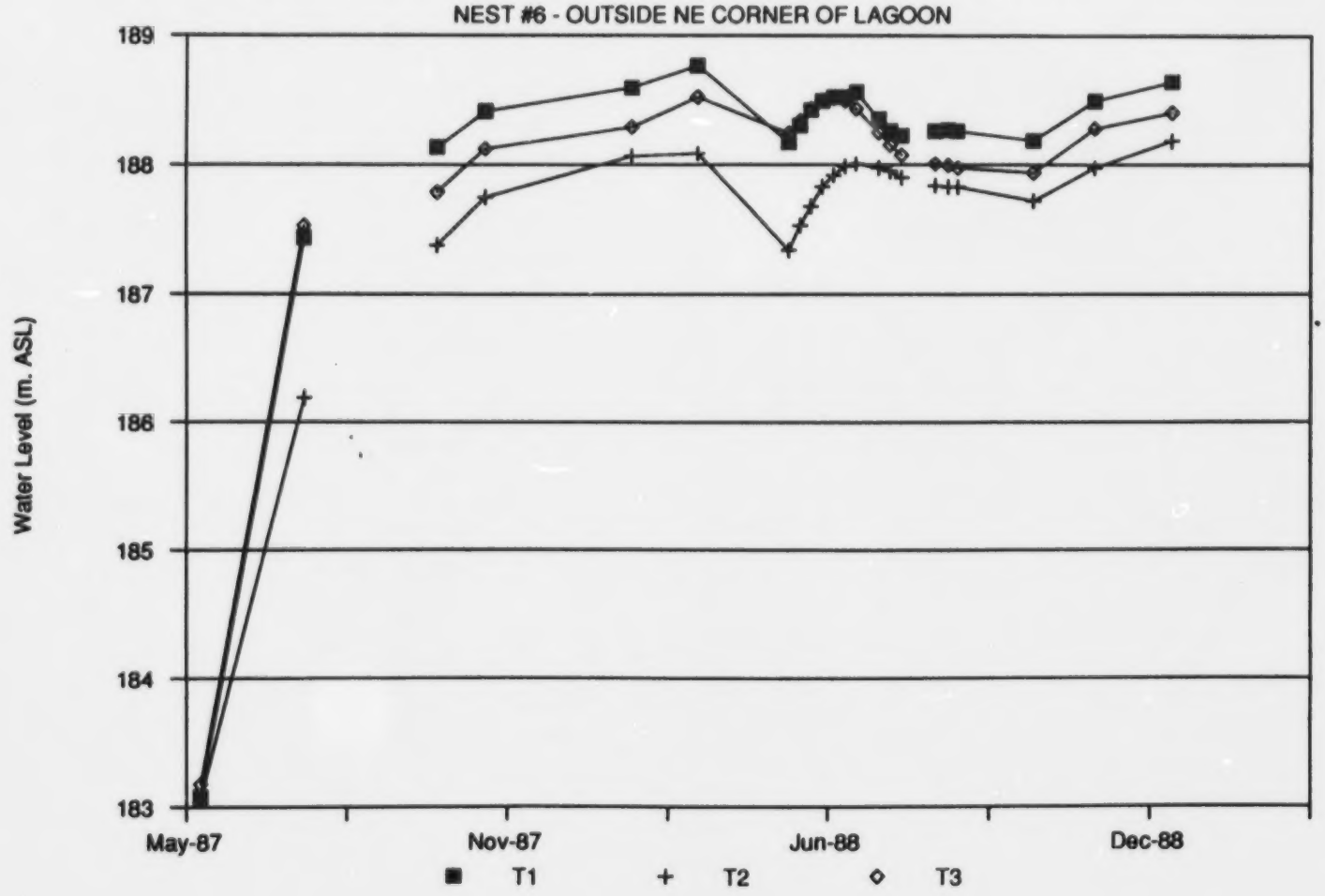

FIGURE 7

WATER LEVEL CHANGES AT NANTICOKE TGS

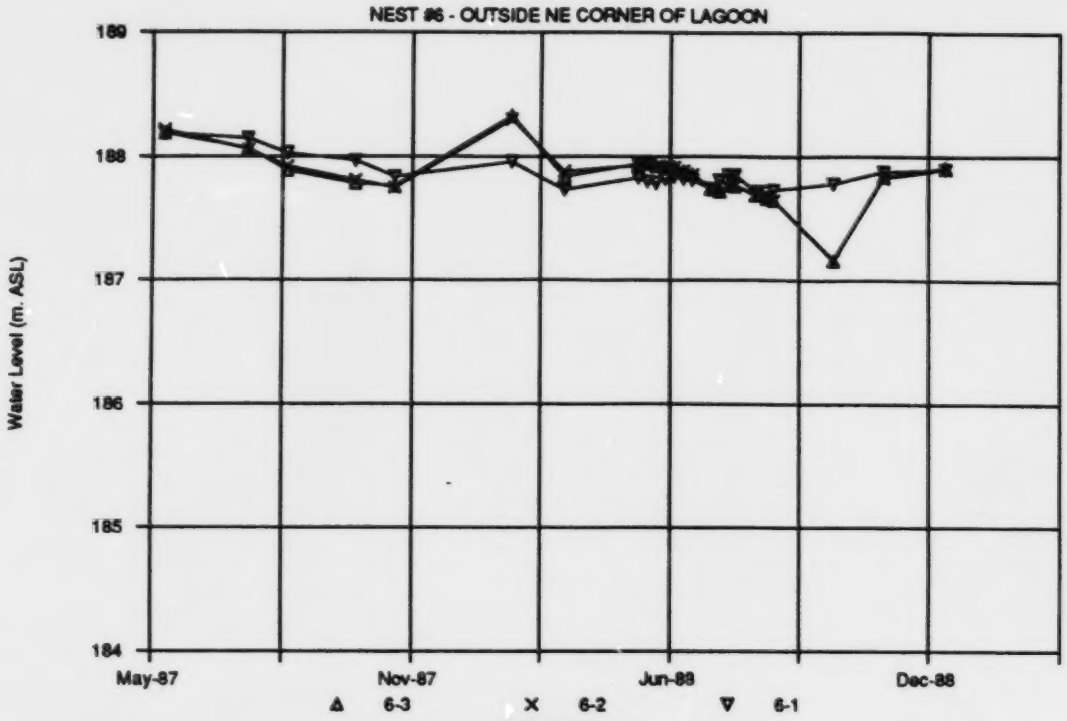

FIGURE 8a

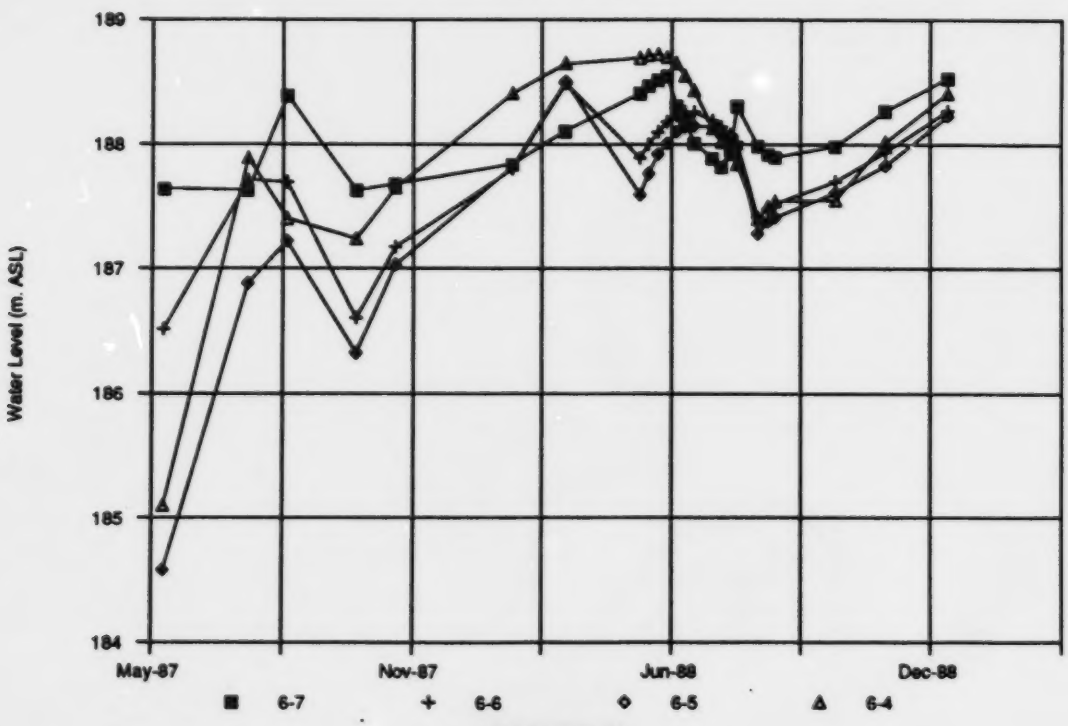

FIGURE 8b

TOTAL HEAD PROFILES FOR ALL NESTS AT NANTICOKE TGS

(water level data for January 5th, 1989)

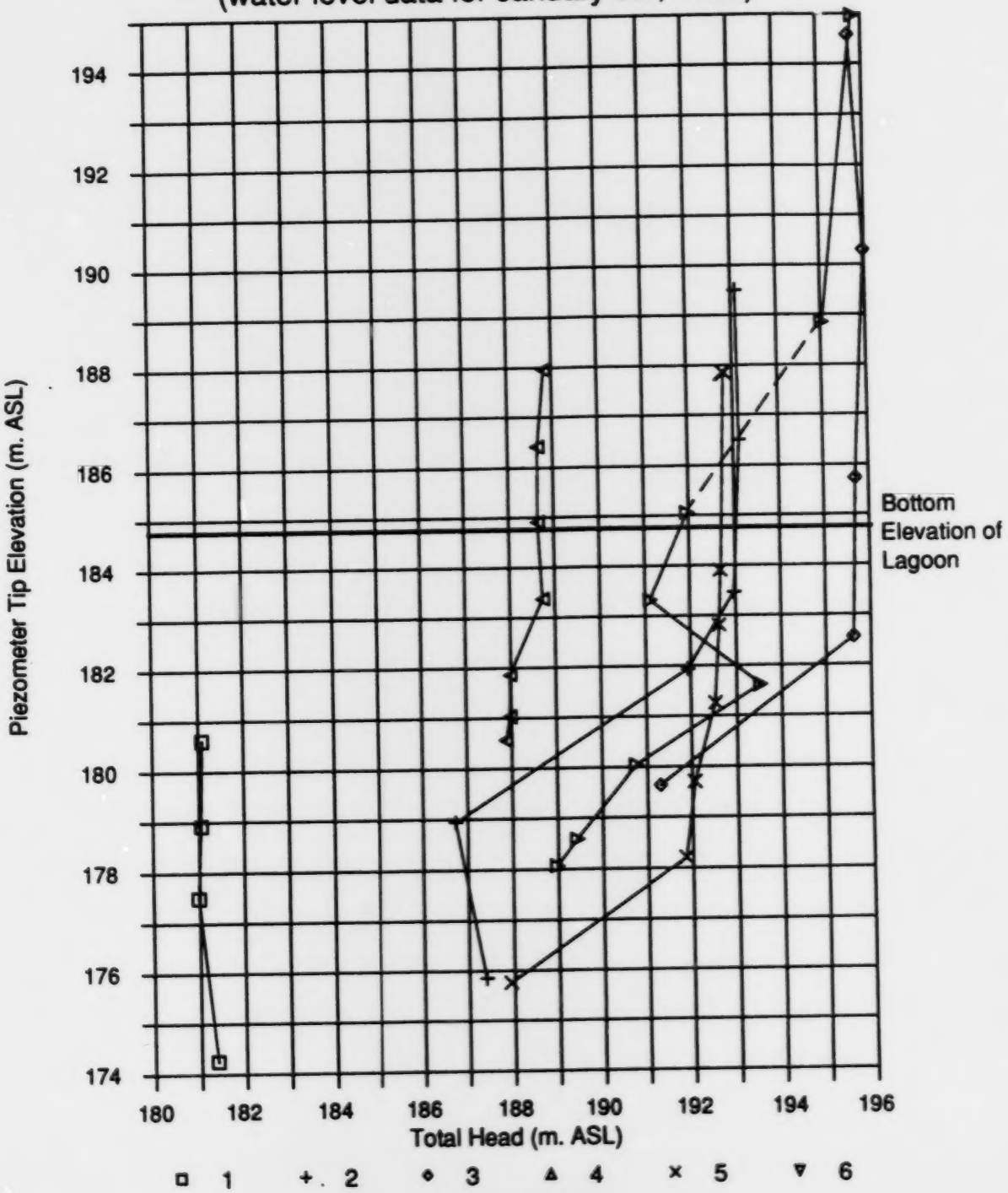

FIGURE 9

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APPENDIX

Rising Head Test Plots

This Appendix contains the Hvorslev plots for each rising head test performed in piezometer Nests #1 to #6. This graphical method of analyzing field recovery data is described in detail in Hvorslev (1951). Briefly, the method entails plotting field recovery data, H-h, normalized to $H-H_o$, on a logarithmic scale versus elapsed time on an arithmetic scale where:

H = equilibrium hydraulic head, t =
H_o = hydraulic head after bailing, t = 0
h = hydraulic head during recovery

This type of semi-logarithmic plot should ideally result in the data points falling along a straight line with its origin at $(H-h)/(H-H_o) = 1$ and $t = 0$.

The basic time lag, T_o, is the time that would be required for the complete equalization of the hydraulic head difference if the original rate of inflow were maintained. The value of T_o is determined from the straight line on the semi-logarithmic plot when the head ratio, $(H-h)/(H-H_o) = 0.37$. For practical purposes, the log (head ratio) was plotted versus time on all graphs in the Appendix. With this type of scale, the basic time lag was determined at log (head ratio) = -0.432. All T_o-values are tabulated in Table II.

For the Casagrande-type piezometers used in this investigation, Hvorslev provided the following expression for determining the formation hydraulic conductivity:

$$K = \frac{r^2 \ln (L/R)}{2LT_o} \qquad (1)$$

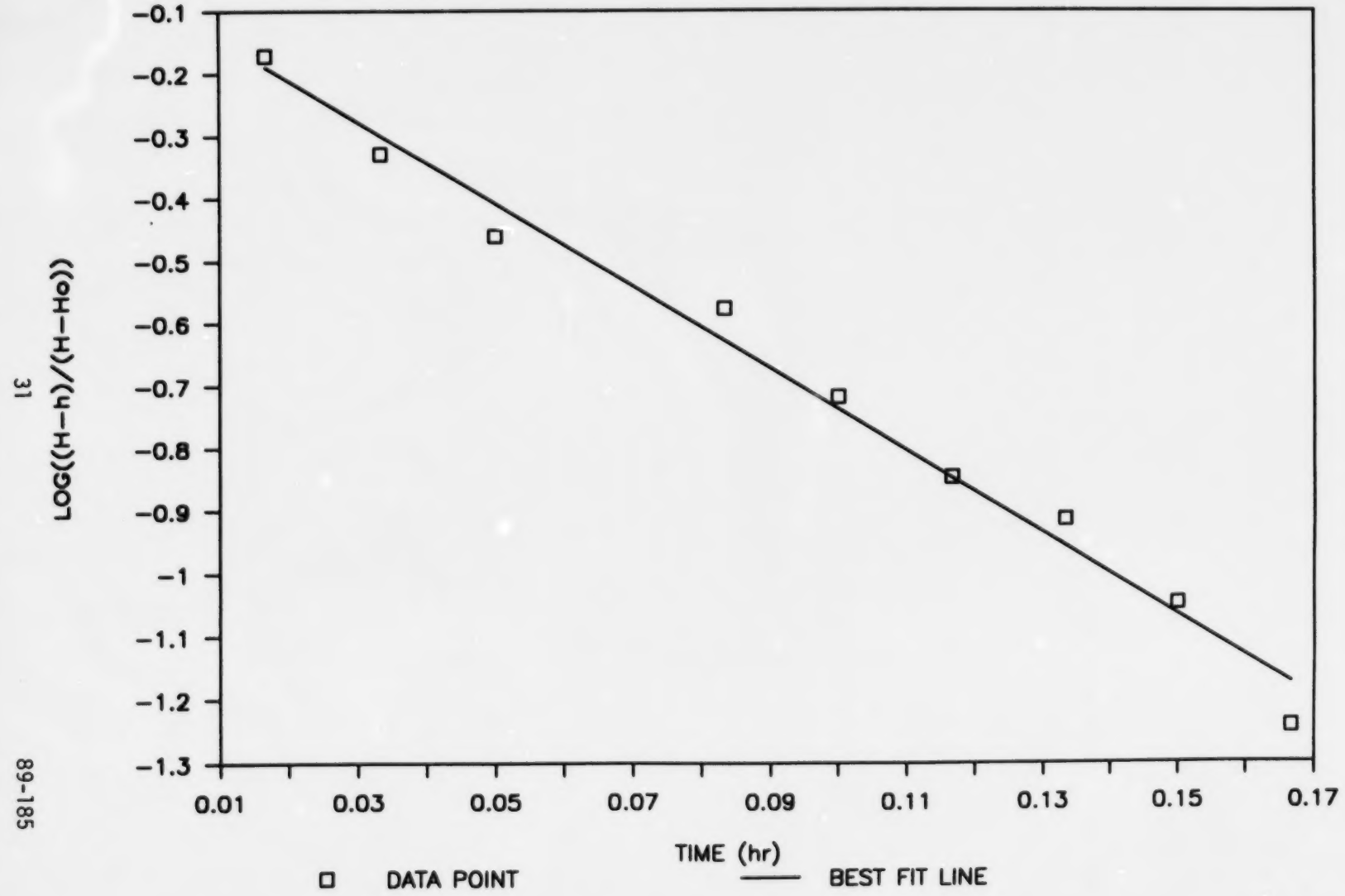
where, r = inside radius of piezometer pipe
R = radius of piezometer intake (includes sand pack)
L = length of piezometer intake
T_o = basic time lag

The results and input data to equation 1 are provided in Table II.

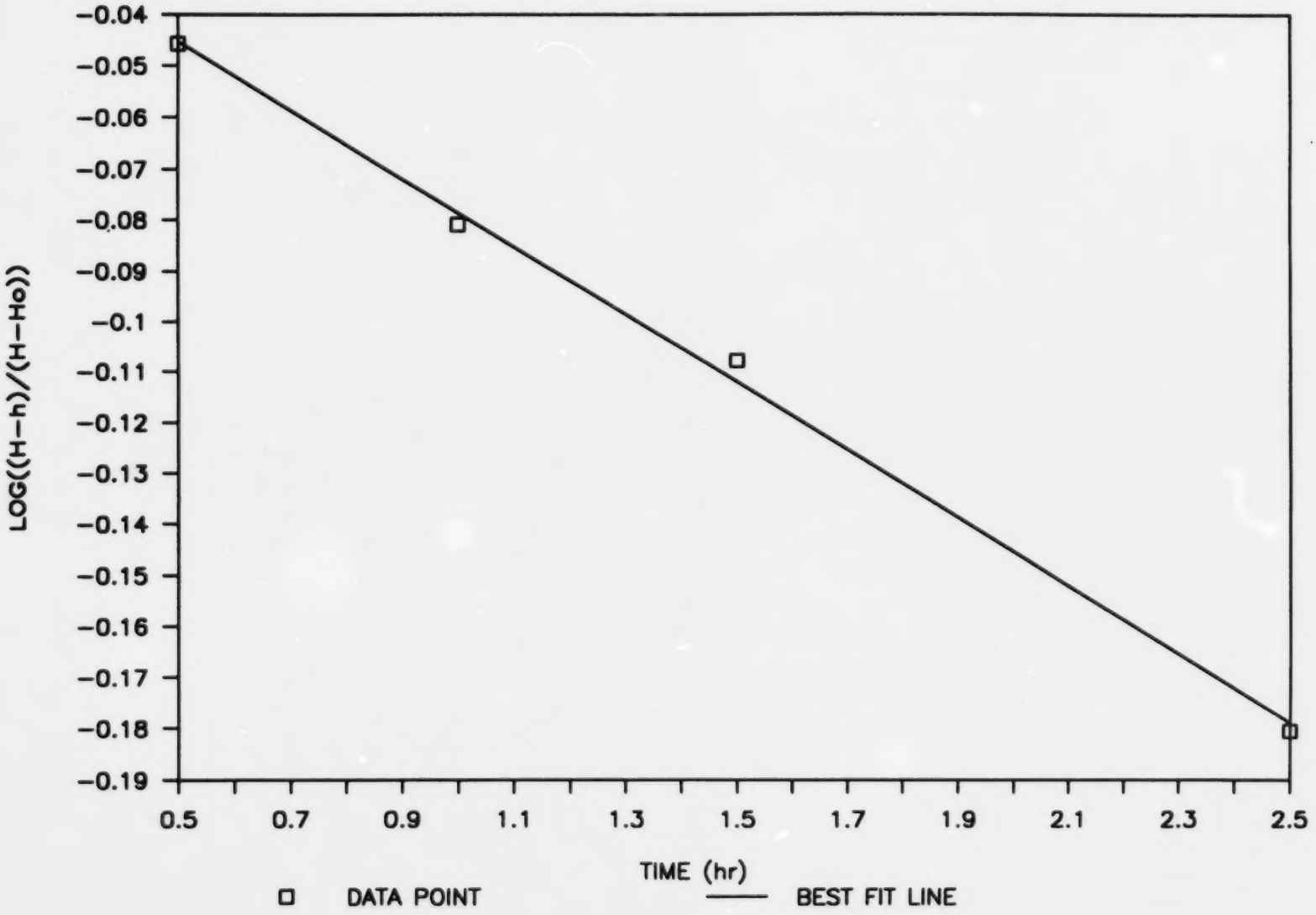
In several cases, especially with the older piezometer Nests #1 to #3, insufficient water level data was collected to allow direct estimates of time lag at a head ratio of 0.37.

In these cases, the straight line plotted through the early time data was extrapolated to a head ratio of 0.37 and then the time lag determined at this point. The recovery data from Nest #5 appears to have been influenced by fluctuating water levels in the closest ash settling cell. In this case, the basic time lag was also determined by extrapolating the early time data.

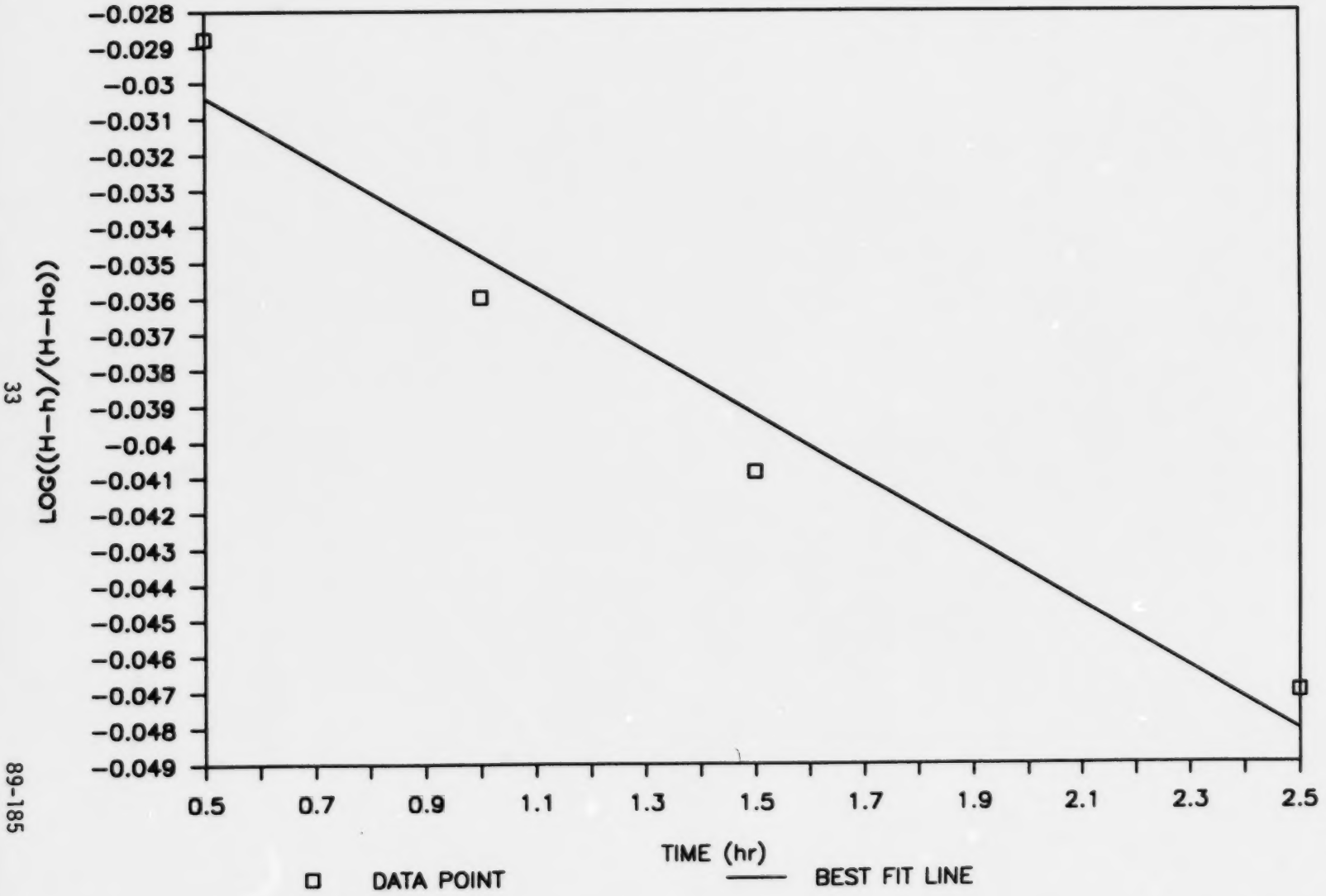
In the cases where the straight line portion of the curve does not extend to near the origin of the plot, notably for piezometer #6-1, 6-5 and 6-6, a different graphical method was used as suggested by Hvorslev. The straight line portion of the curve was translated to a new position from where it could intersect the origin and the basic time lag determined from this new line. The basis for this new construction is the assumption that the early portion of the recovery data was erroneous due to an effect such as gas bubbles in the soil near the intake, which would increase the time lag by decreasing the local permeability (Hvorslev, 1951).


NANTICOKE PIEZOMETER #1-1
LOG((H-h)/(H-Ho))
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
0.01
0.03
0.05
0.07
0.09
0.11
0.13
0.15
0.17
TIME (hr)
DATA POINT
BEST FIT LINE

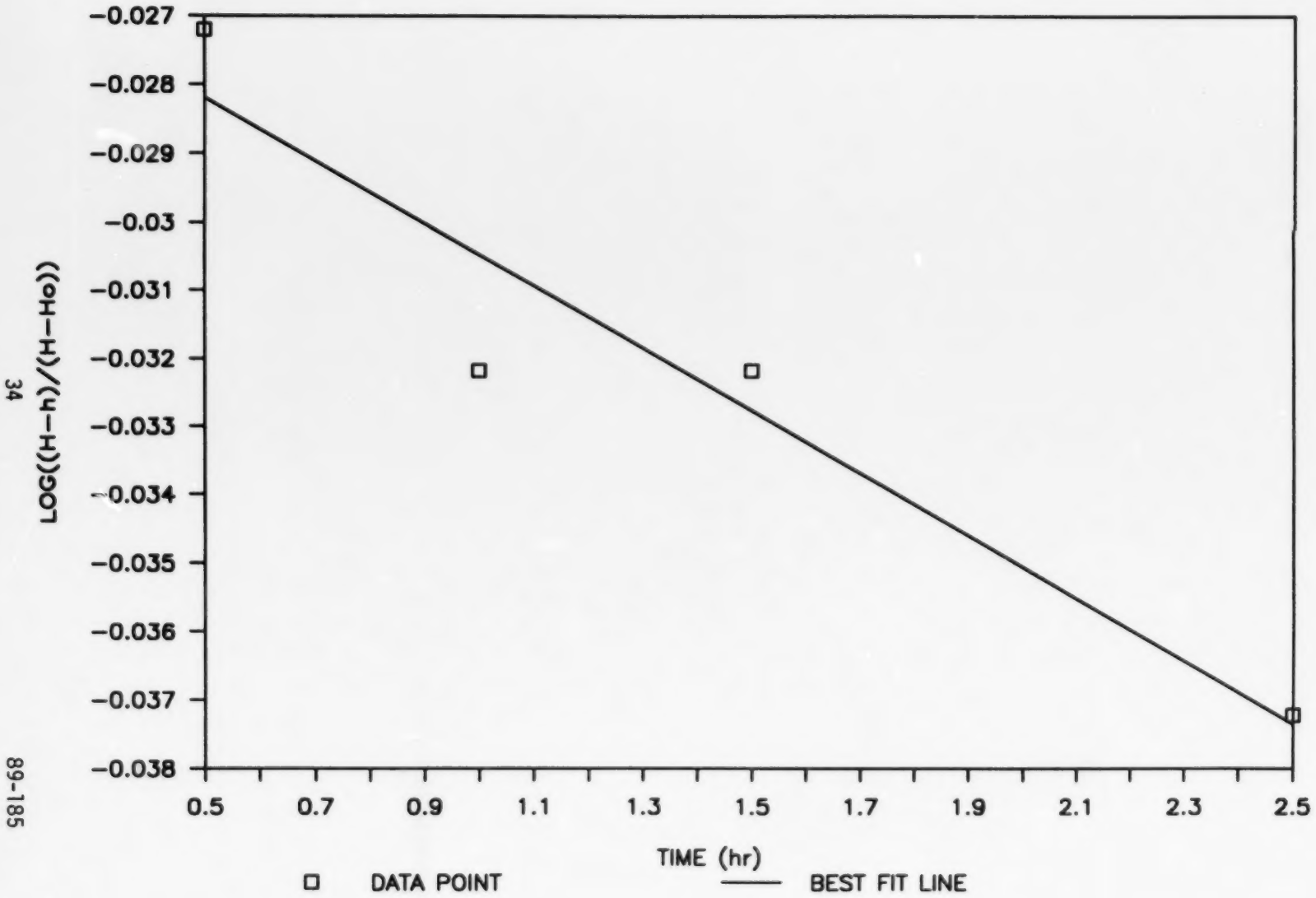
NANTICOKE PIEZOMETER #1-2



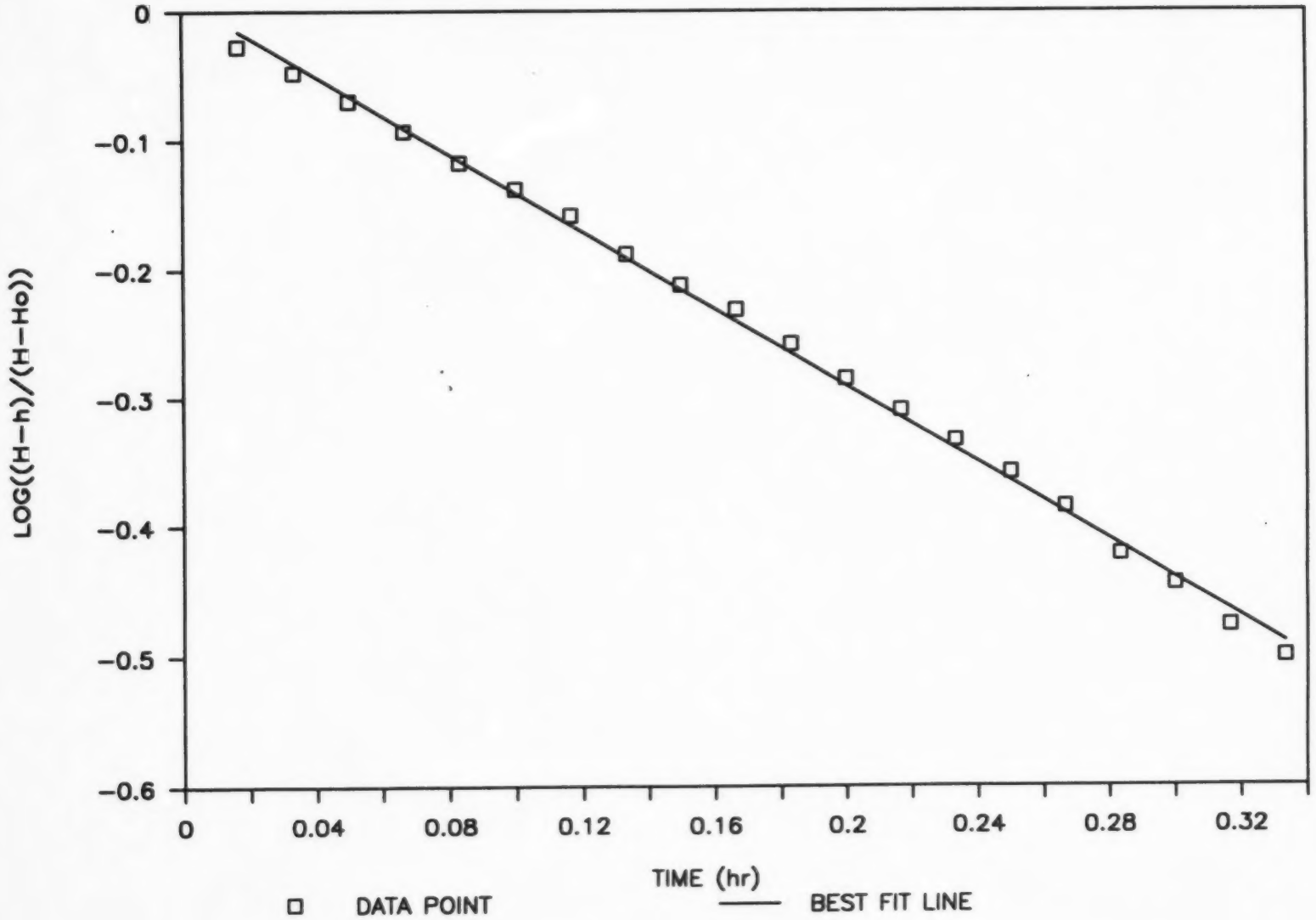
NANTICOKE PIEZOMETER #1-3



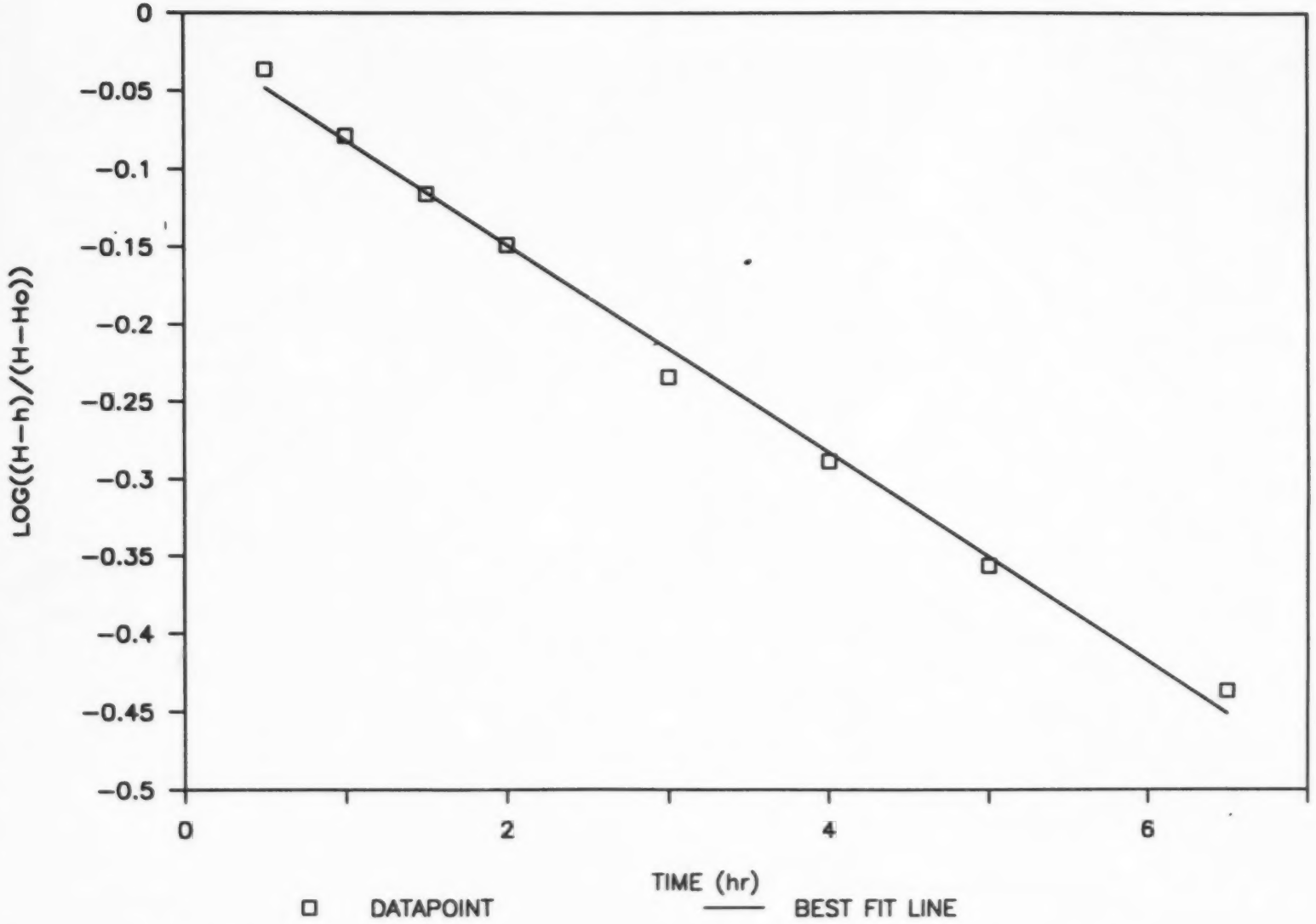
NANTICOKE PIEZOMETER #1-4



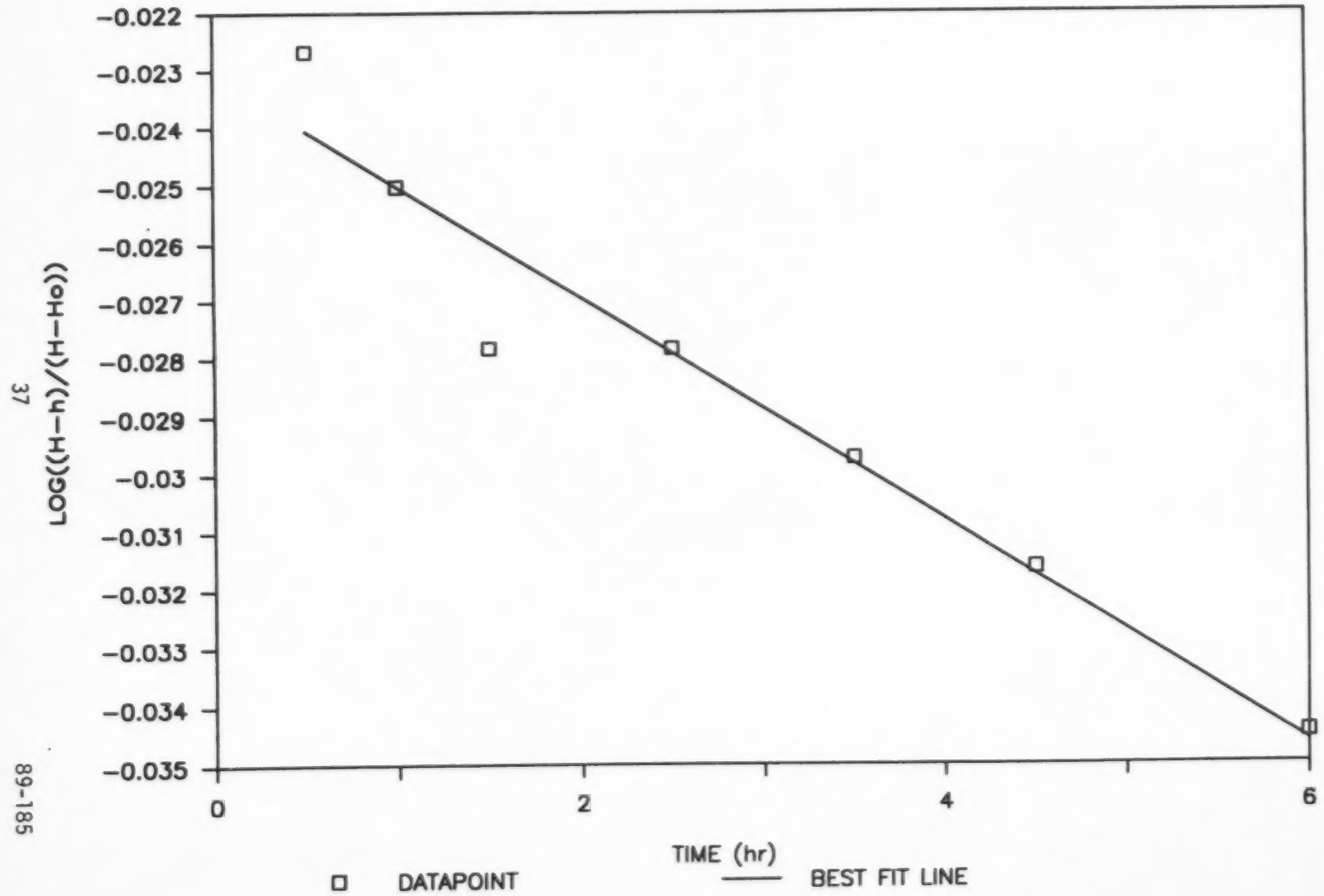
NANTICOKE PIEZOMETER #2-1



NANTICOKE PIEZOMETER #2-2



NANTICOKE PIEZOMETER #2-3



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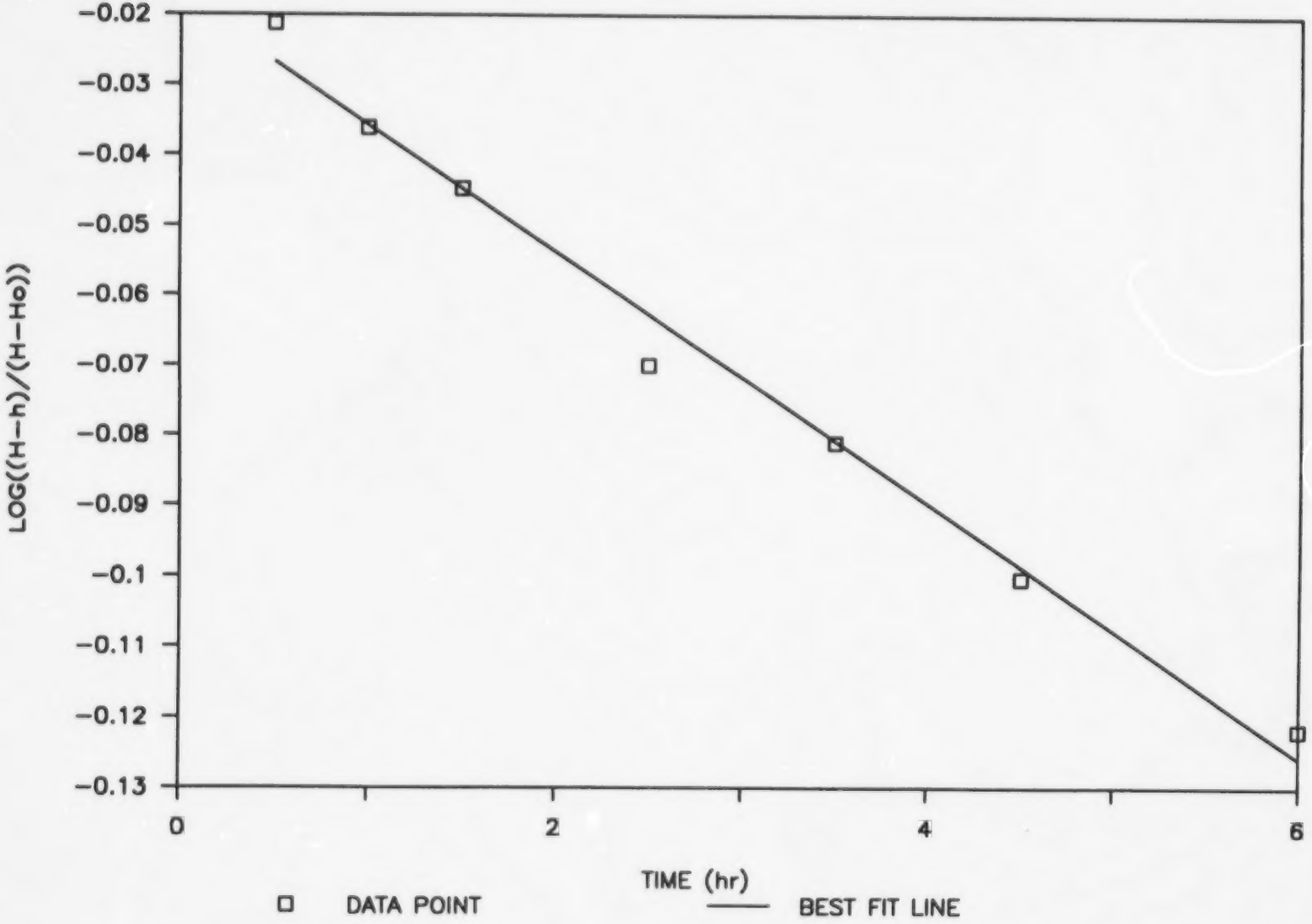
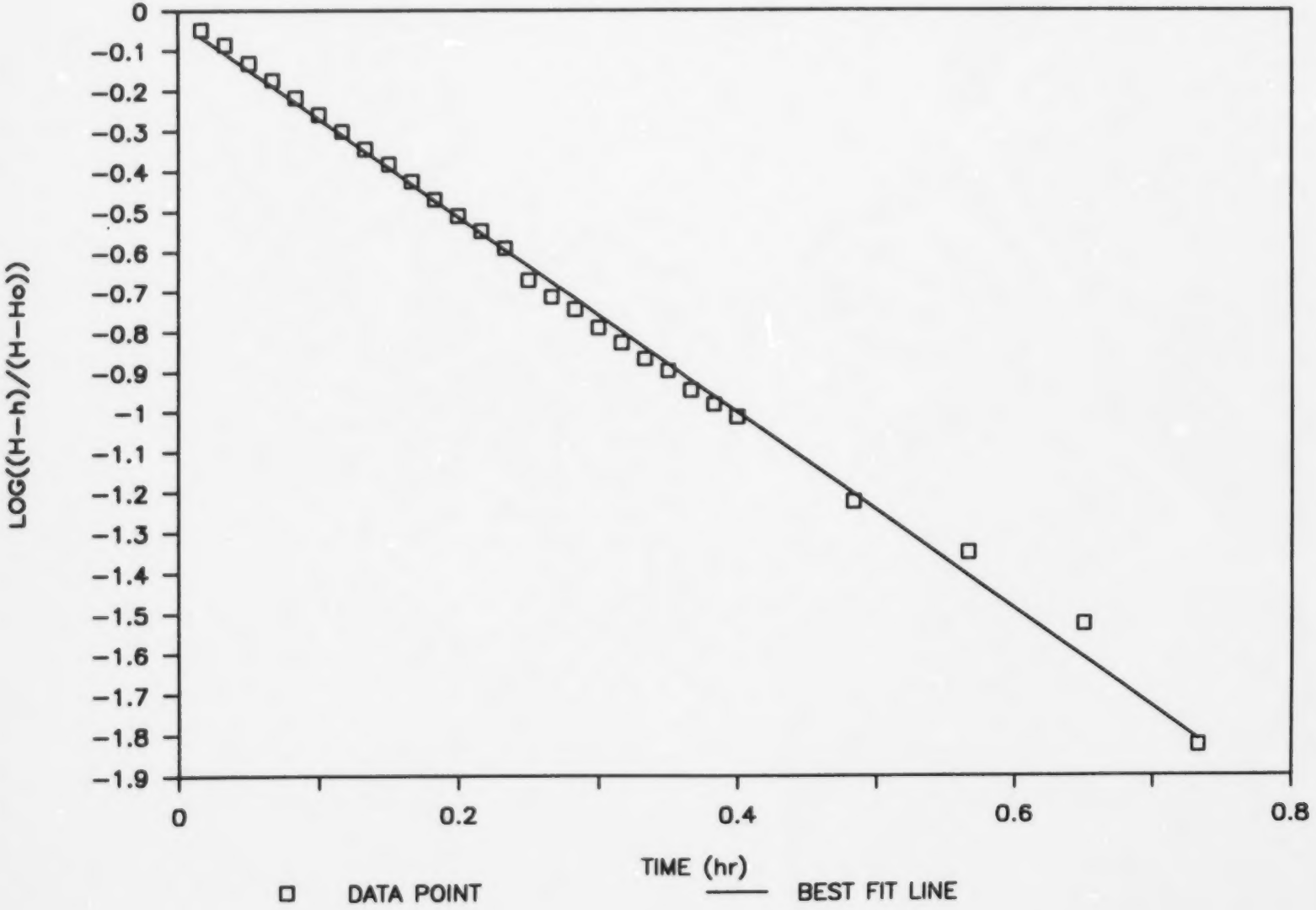
NANTICOKE PIEZOMETER #2-4



NANTICOKE PIEZOMETER #2-5



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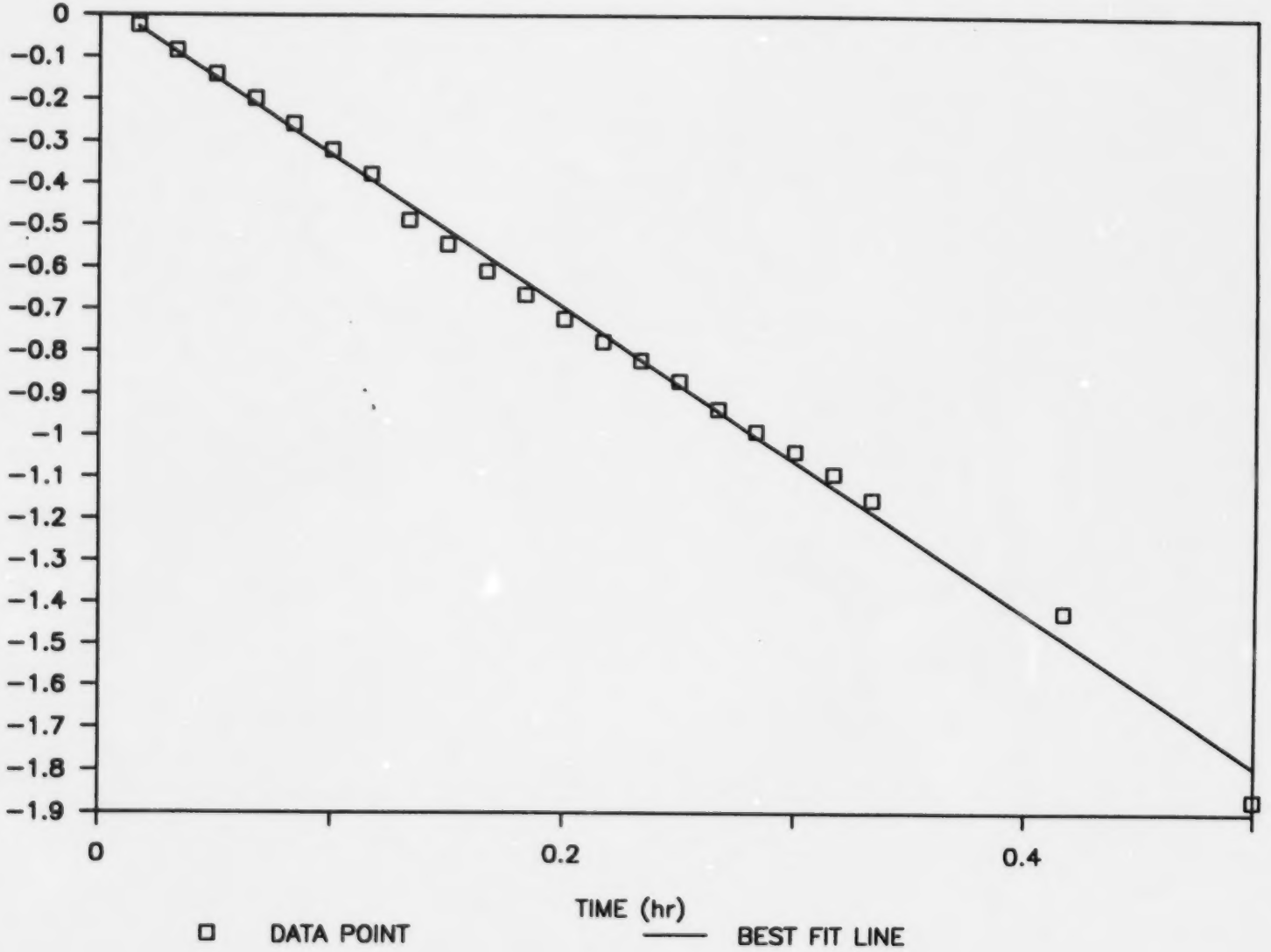
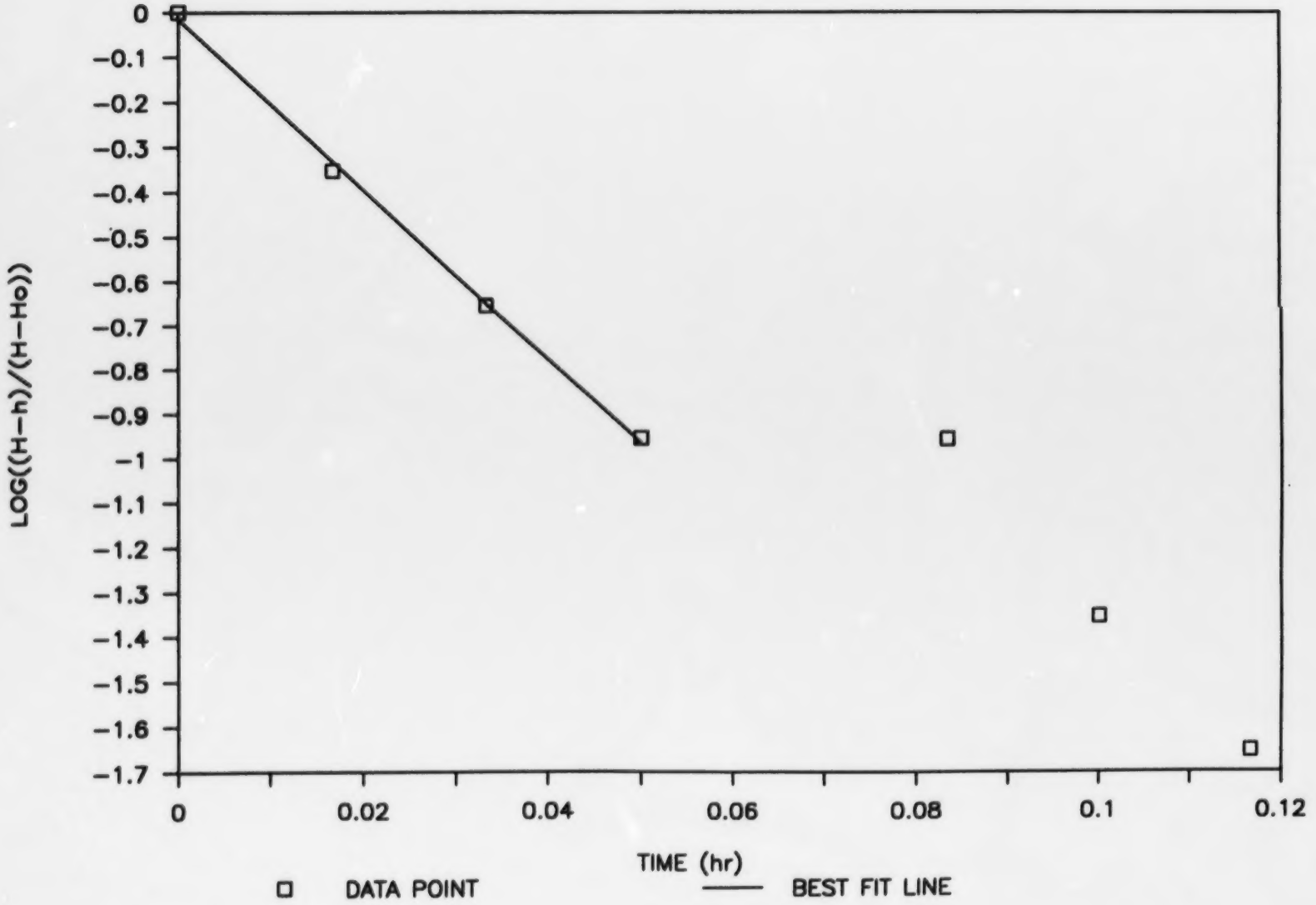
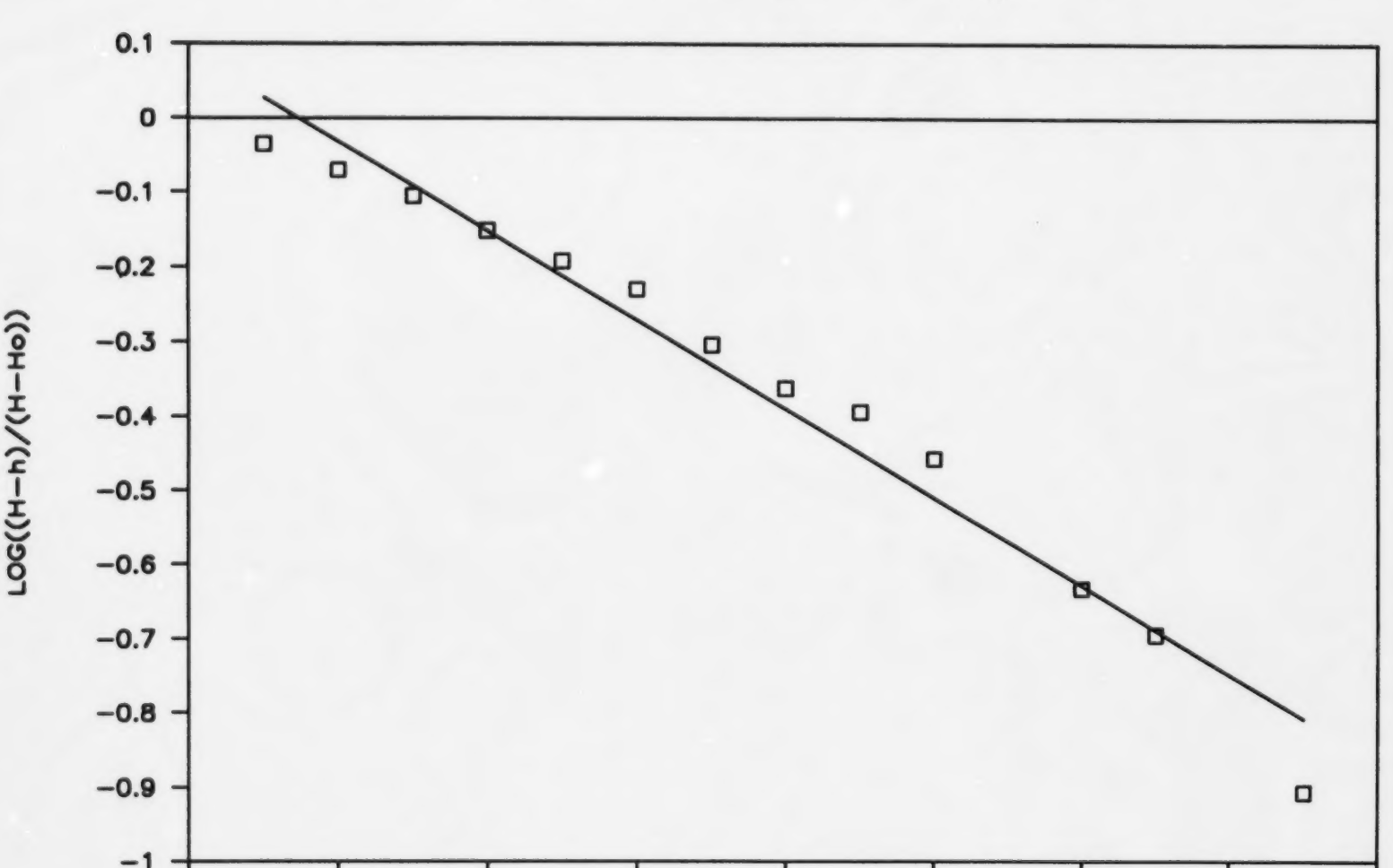
NANTICOKE PIEZOMETER #2-6



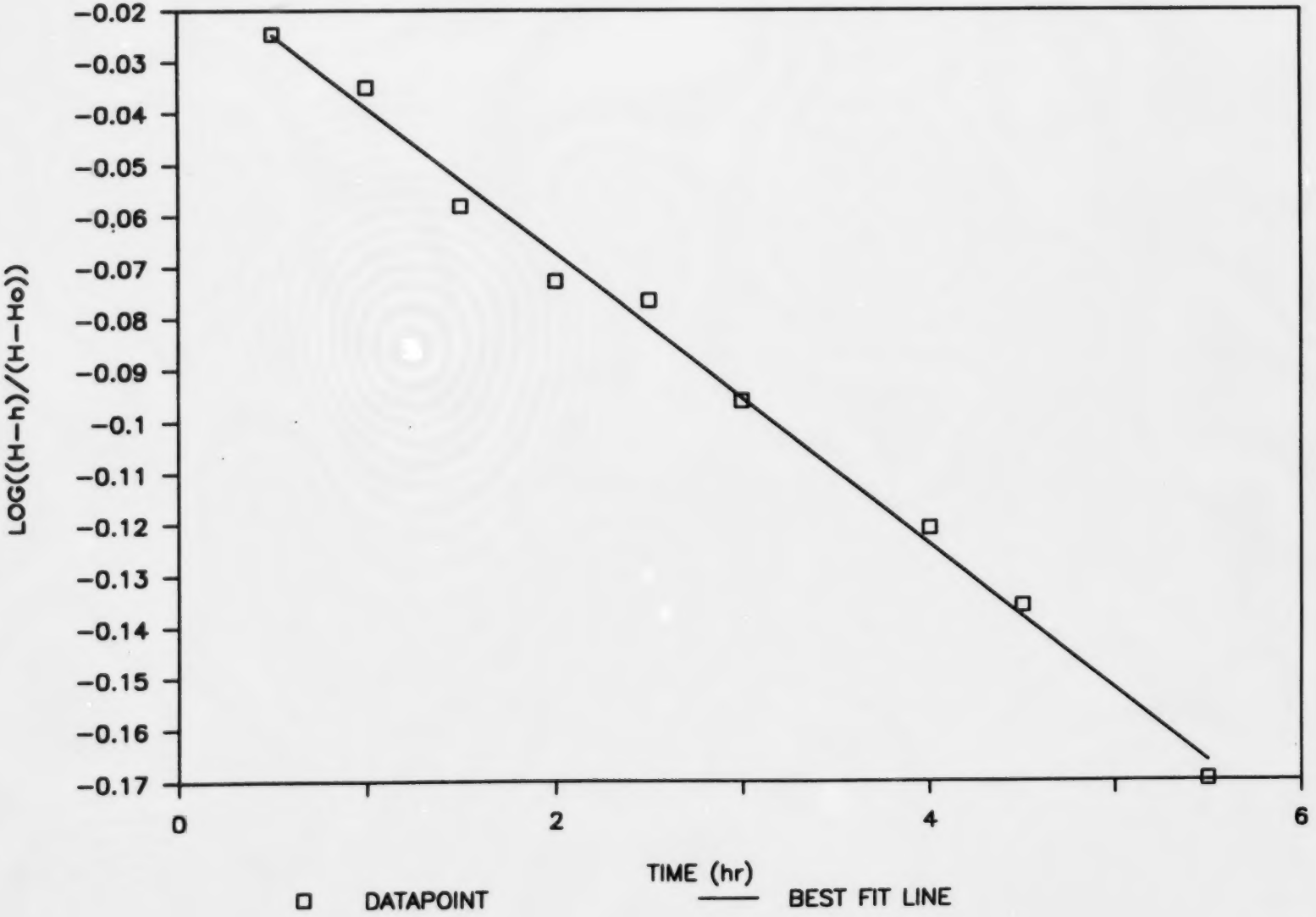
NANTICOKE PIEZOMETER #3-1



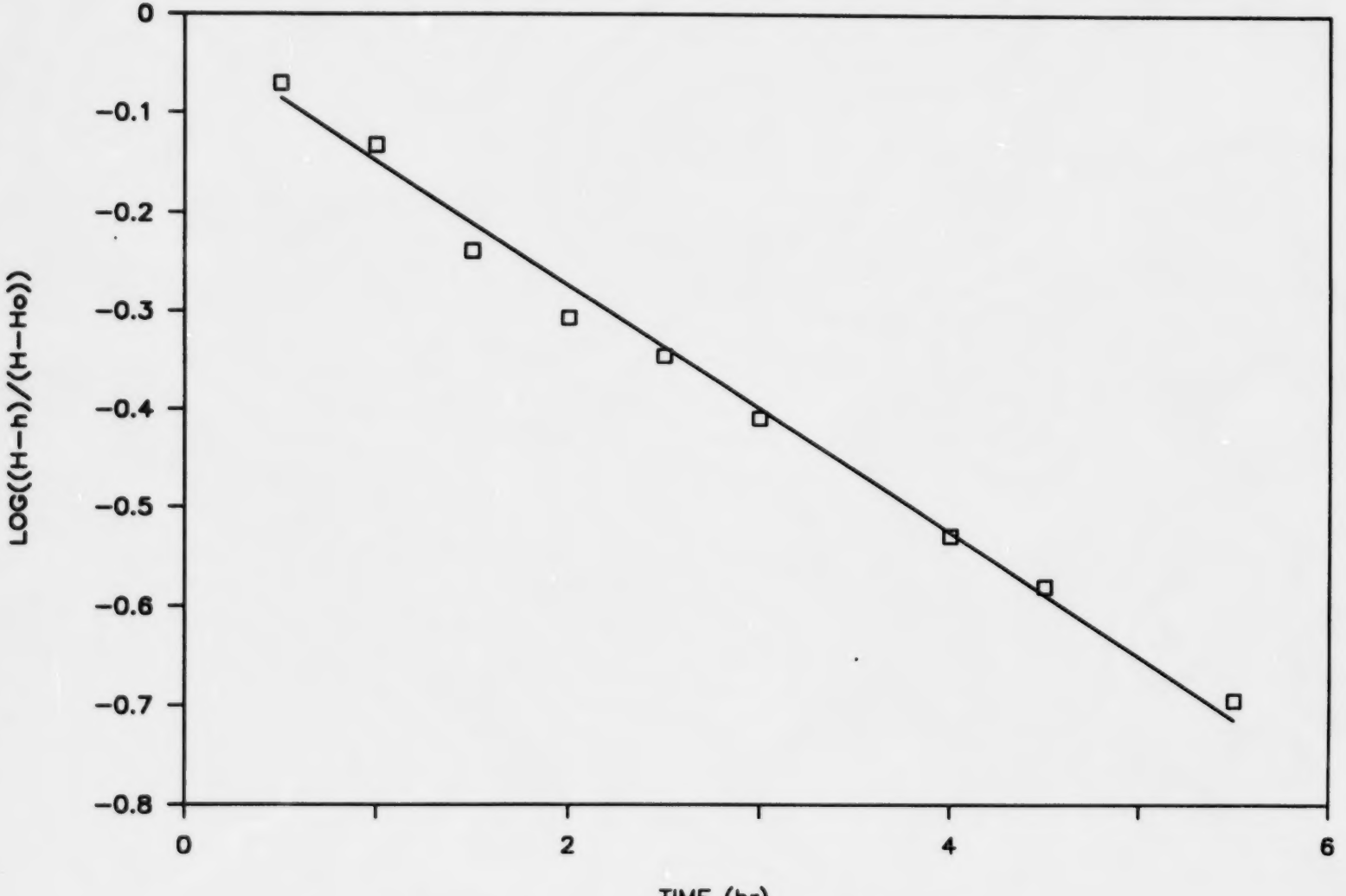
NANTICOKE PIEZOMETER #3-2



NANTICOKE PIEZOMETER #3-3



NANTICOKE PIEZOMETER #3-4



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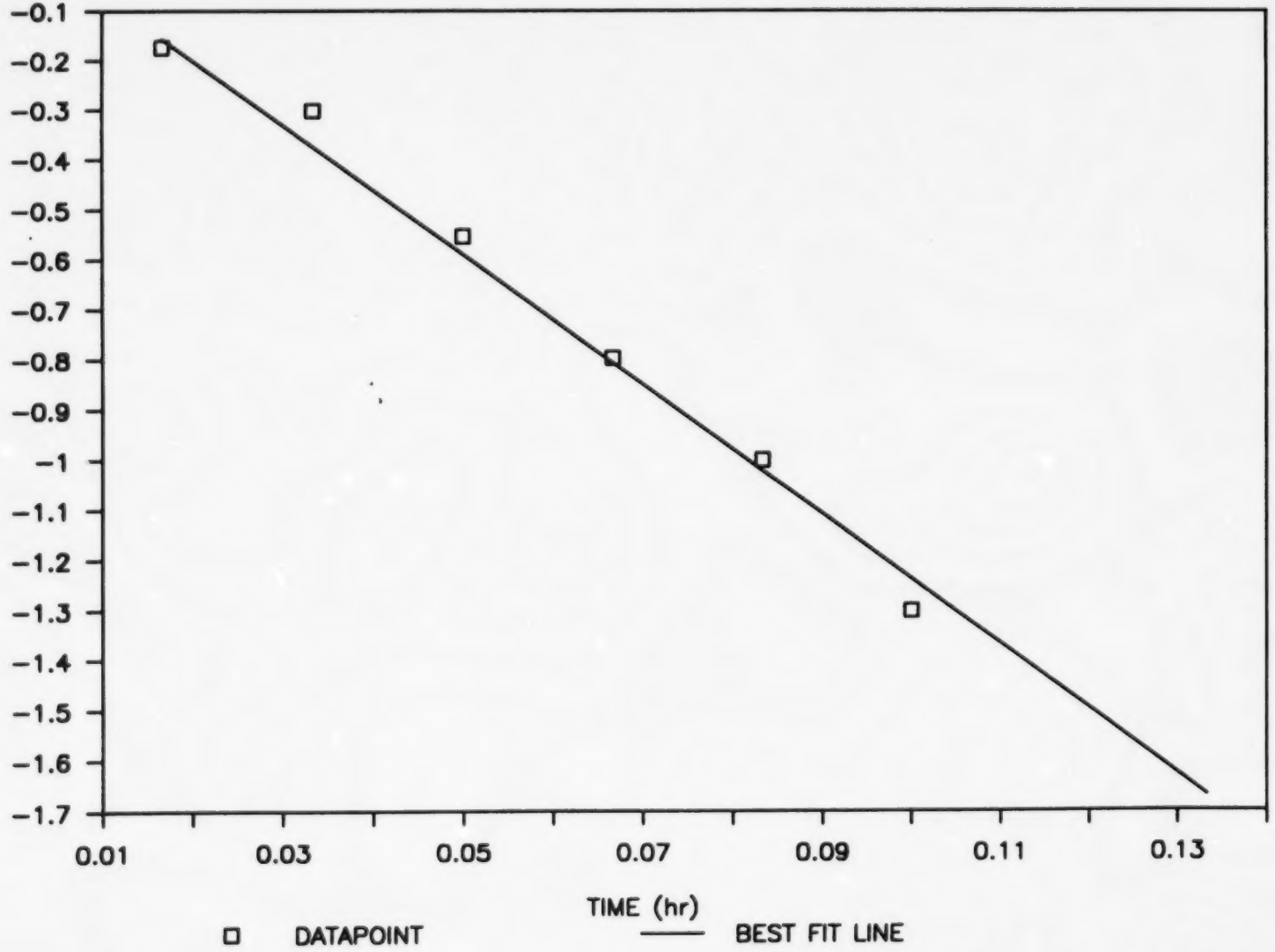
NANTICOKE PIEZOMETER #3-5



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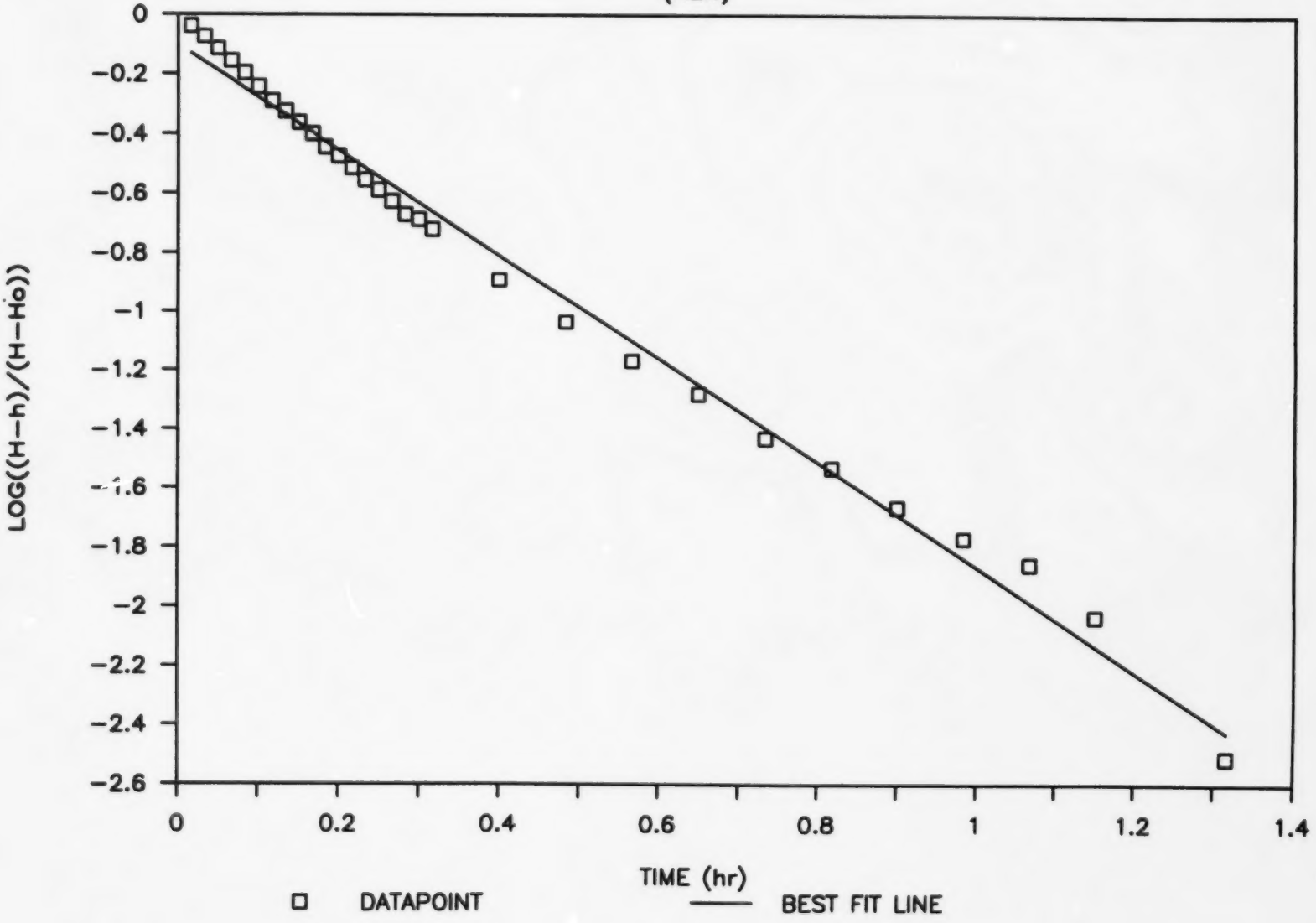
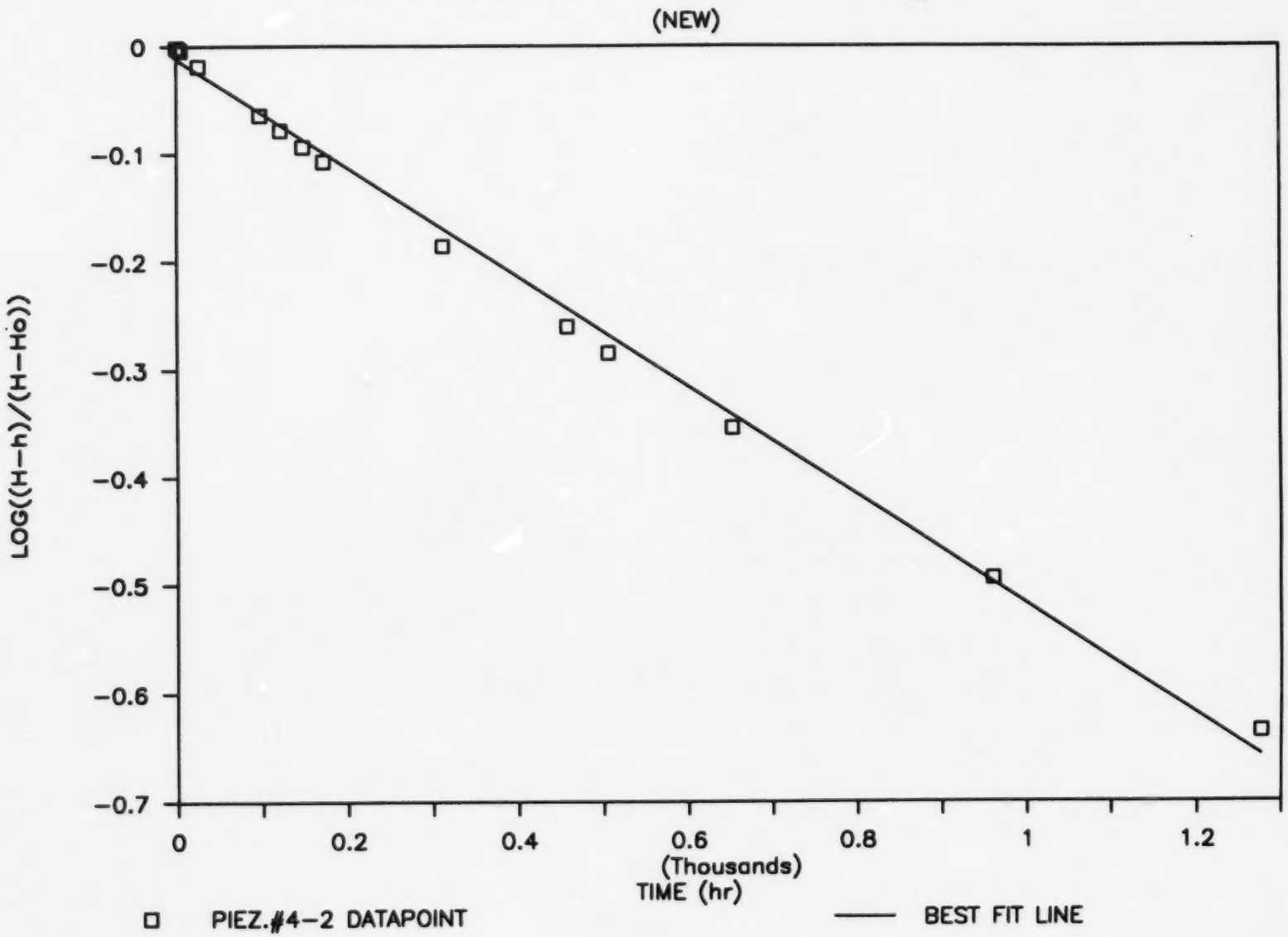
NANTICOKE PIEZOMETER #4-1

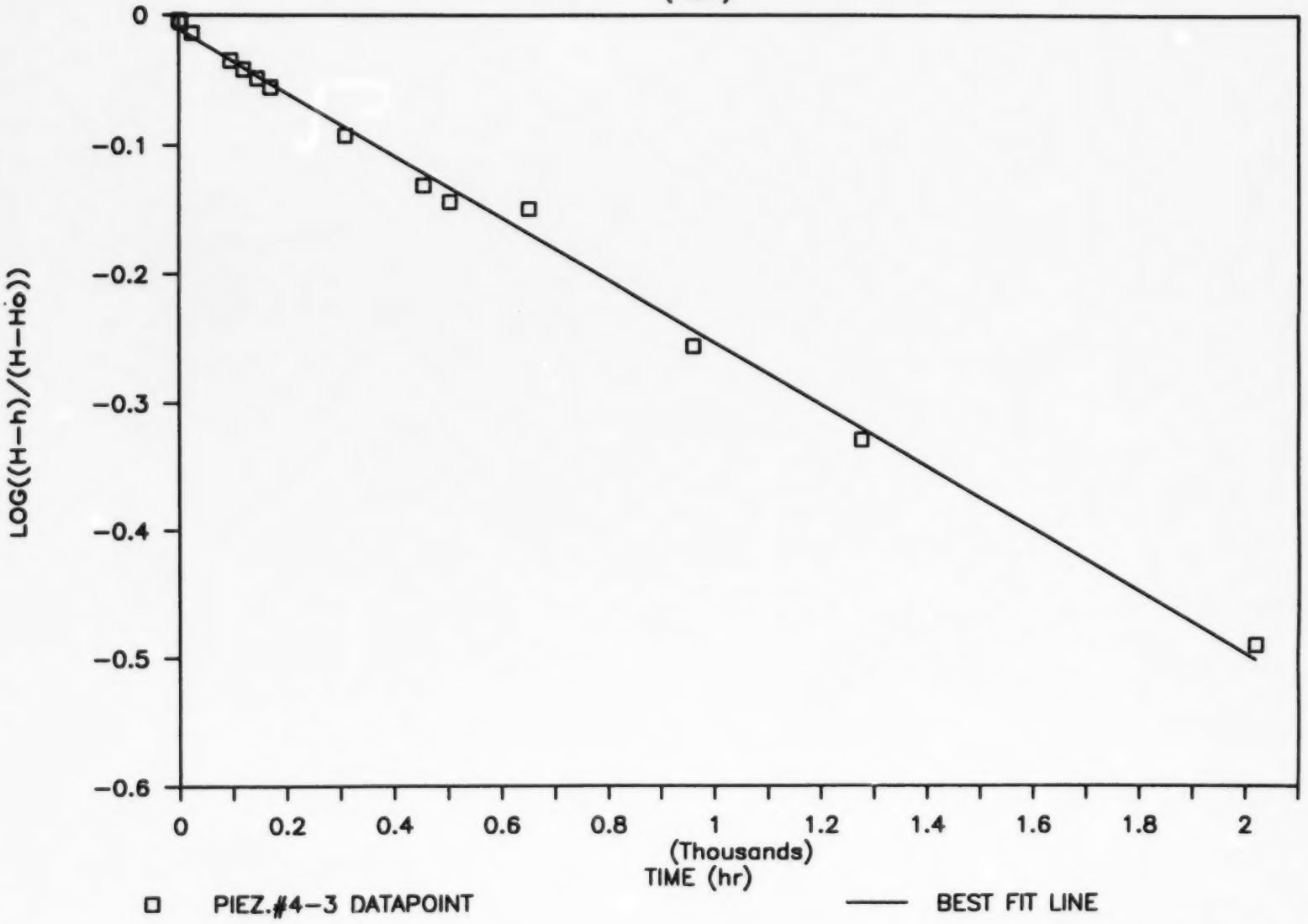
(NEW)




NANTICOKE PIEZOMETER #4-2
(NEW)
LOG((H-h)/(H-Ho))
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
TIME (hr)
PIEZ.#4-2 DATAPOINT
BEST FIT LINE

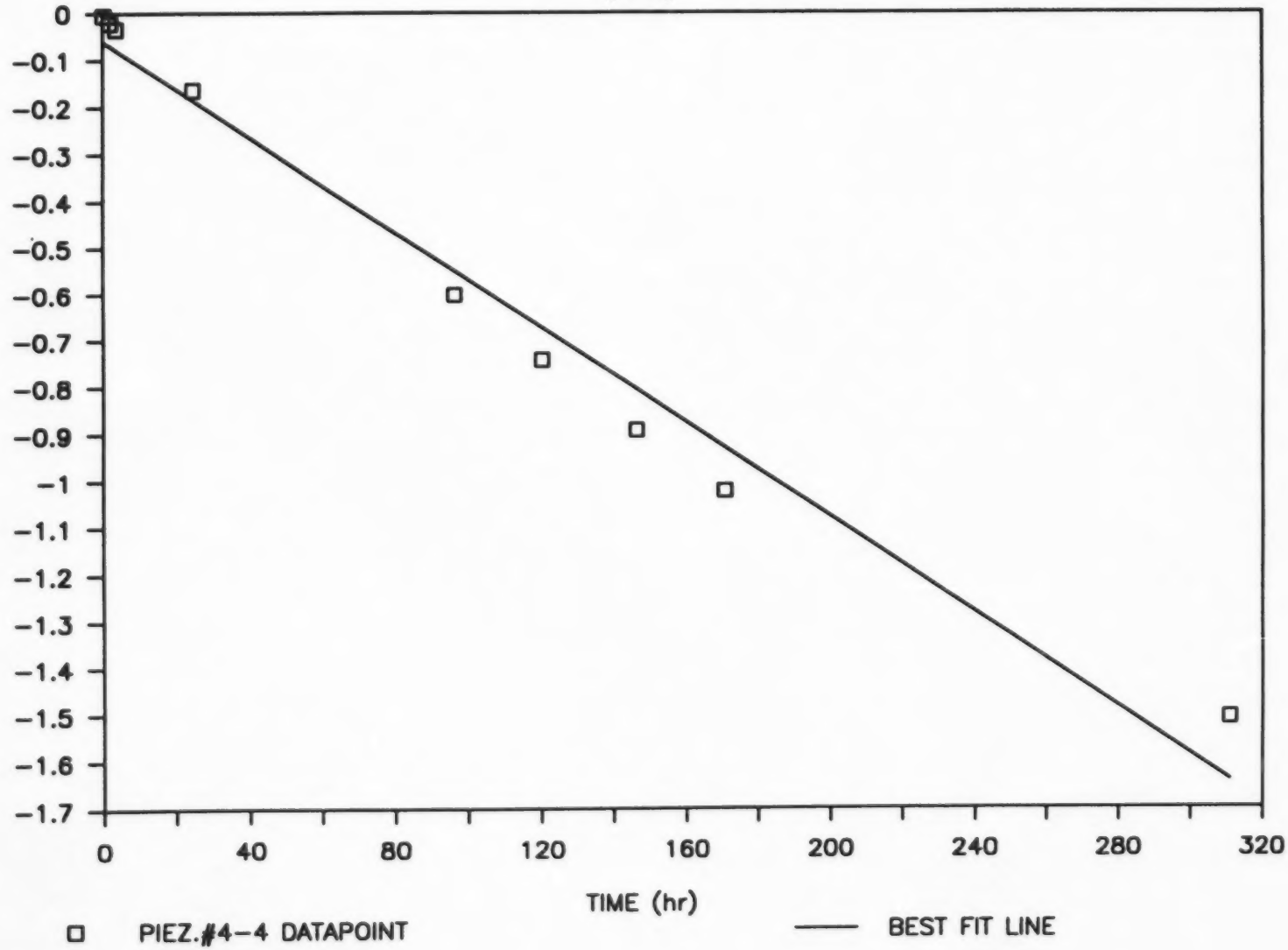
NANTICOKE PIEZOMETER #4-3

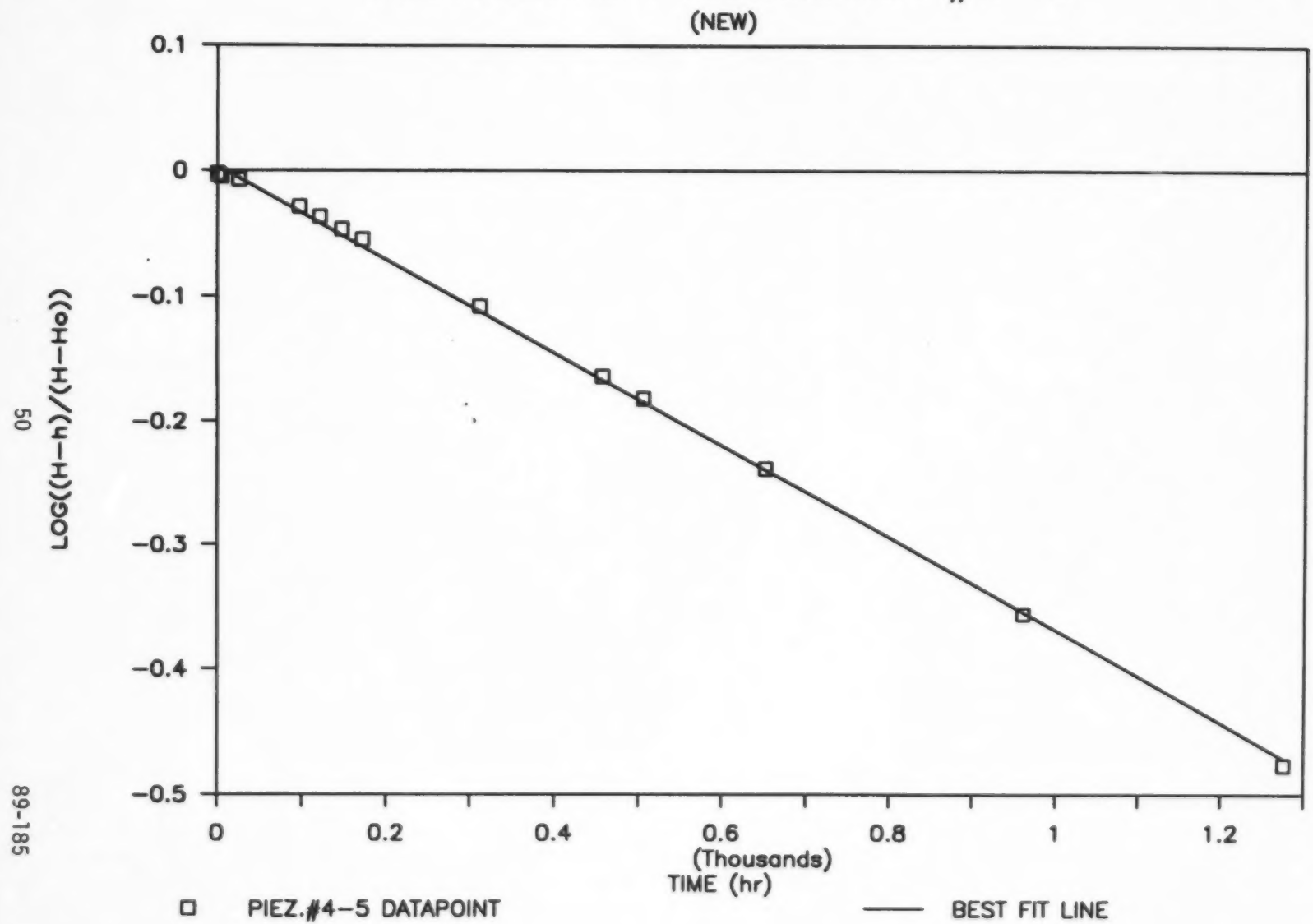
(NEW)

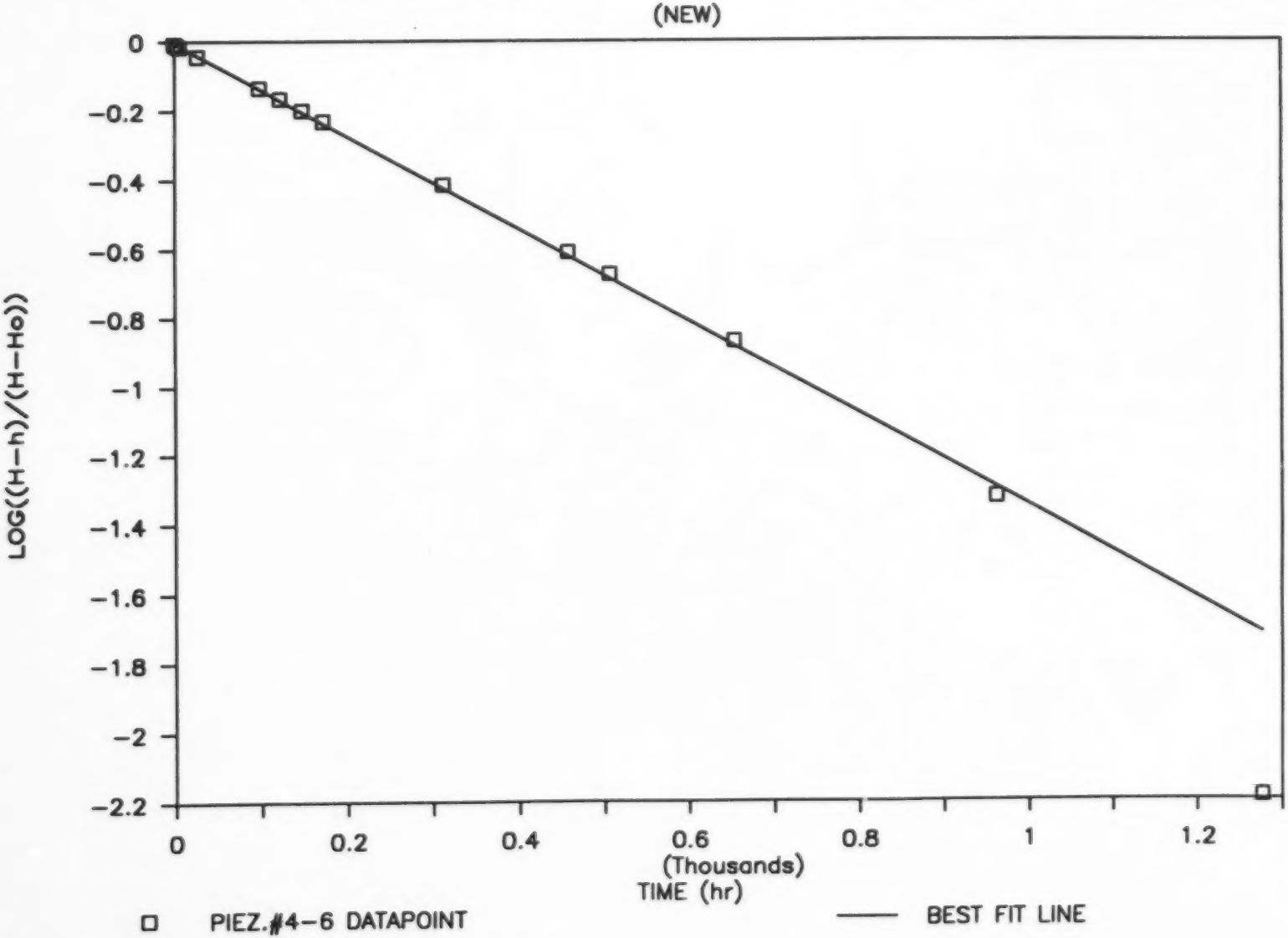


NANTICOKE PIEZOMETER #4-4

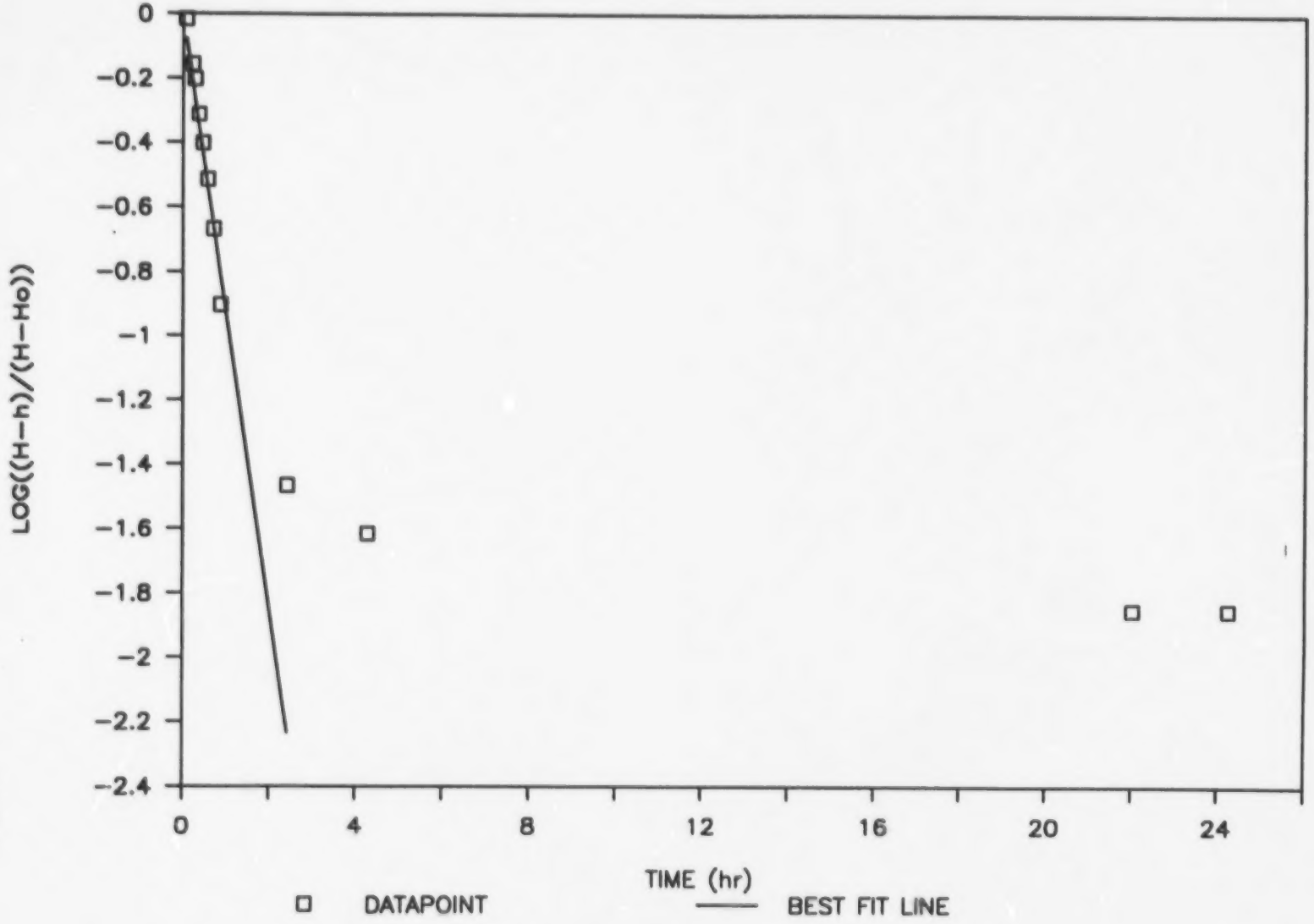
(NEW)




NANTICOKE PIEZOMETER #4-5
(NEW)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
LOG((H-h)/(H-Ho))
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
TIME (hr)
PIEZ.#4-5 DATAPOINT
BEST FIT LINE


NANTICOKE PIEZOMETER #4-6
(NEW)
LOG((H-h)/(H-Ho))
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
-2.2
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
TIME (hr)
PIEZ.#4-6 DATAPOINT
BEST FIT LINE

NANTICOKE PIEZOMETER #5-1



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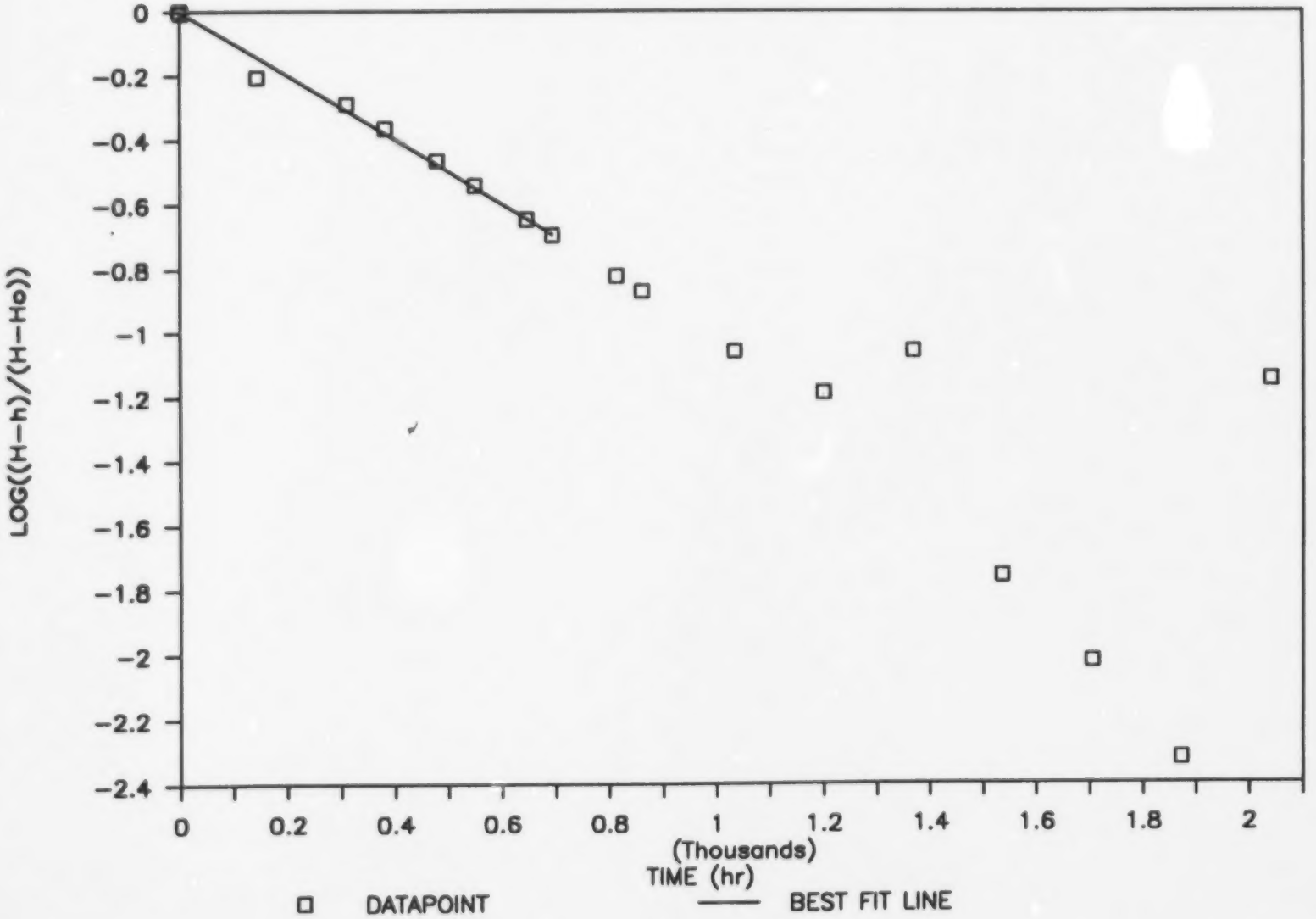
NANTICOKE PIEZOMETER #5-2



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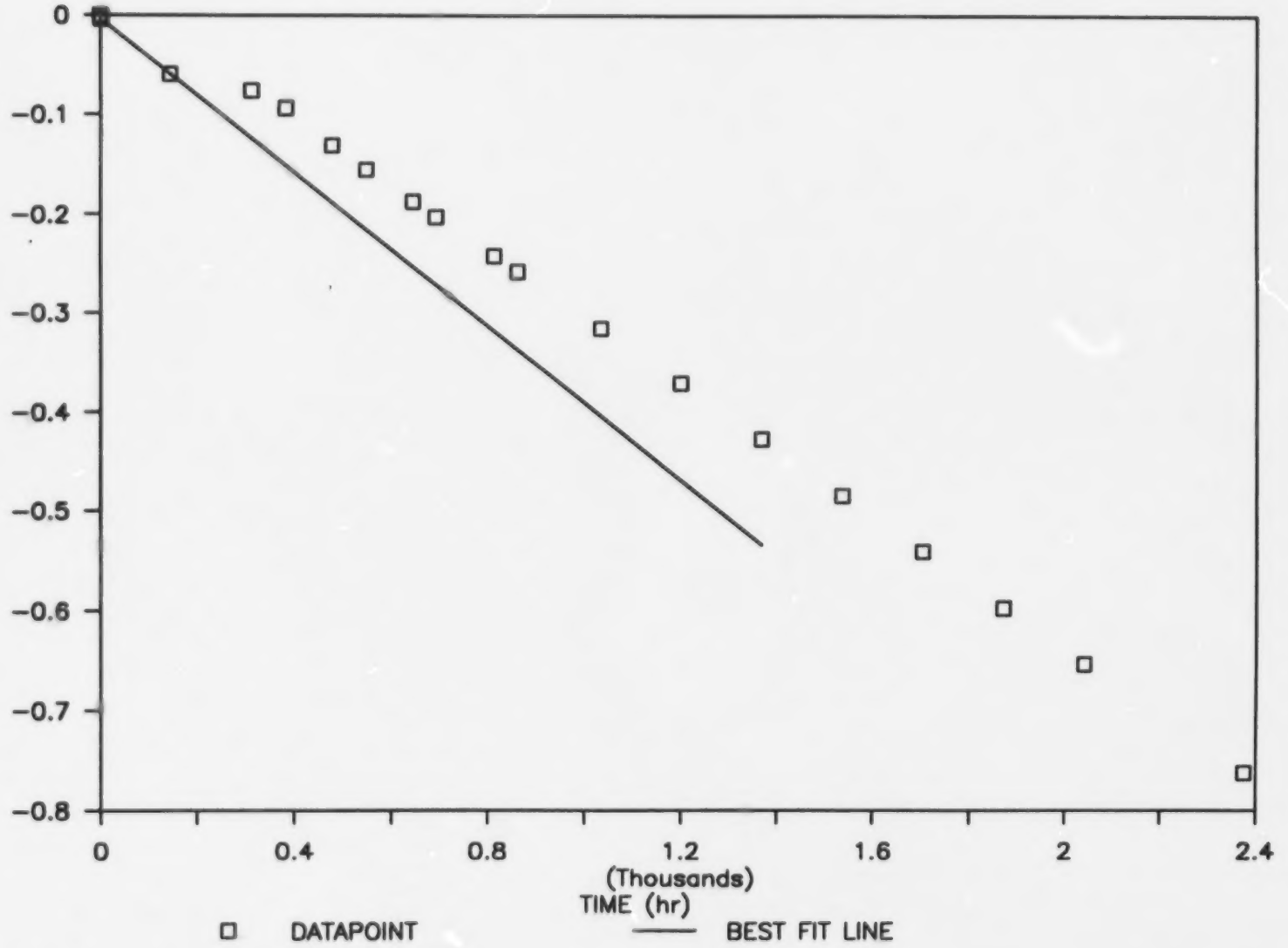
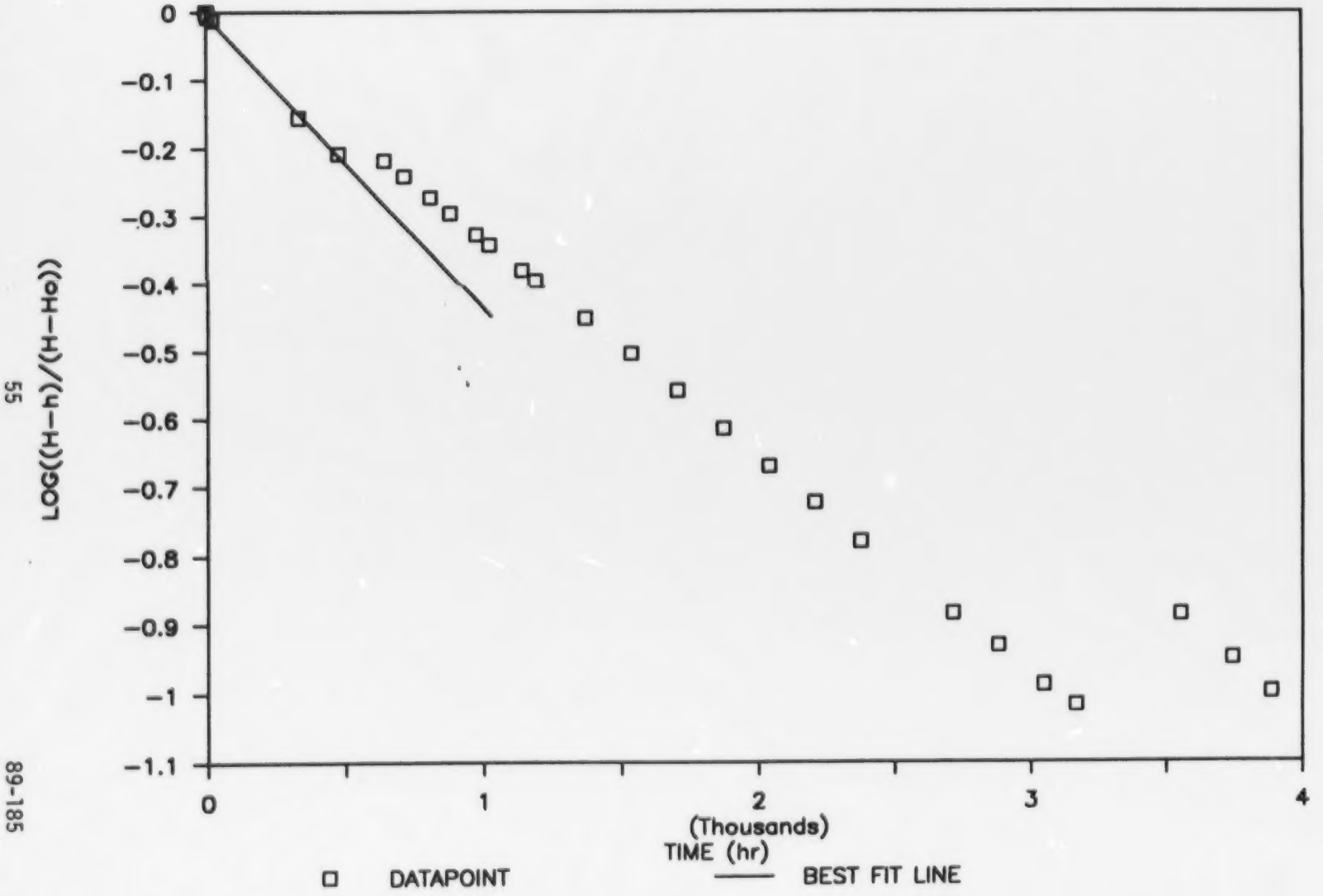
NANTICOKE PIEZOMETER #5-3



NANTICOKE PIEZOMETER #5-4



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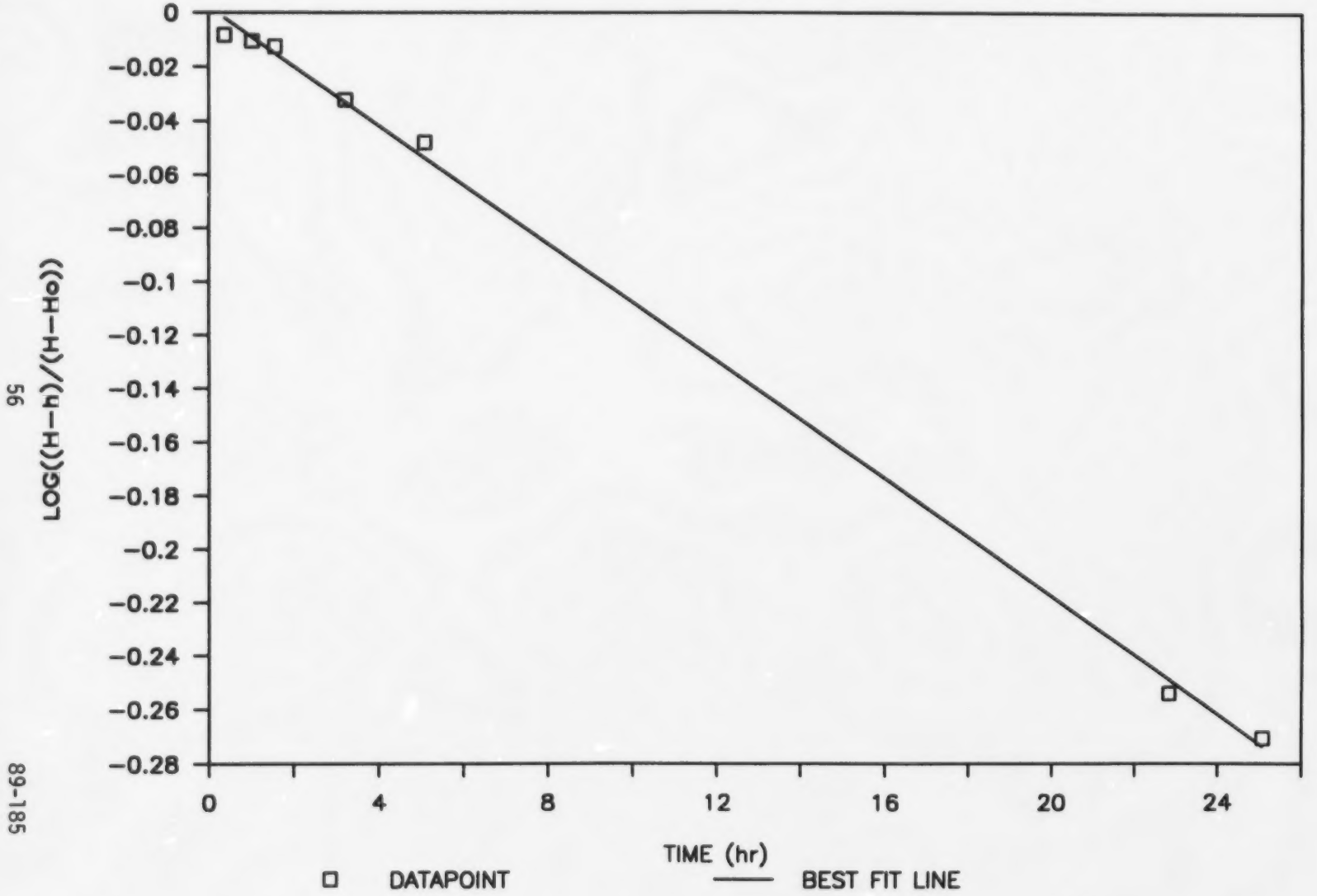
NANTICOKE PIEZOMETER #5-5



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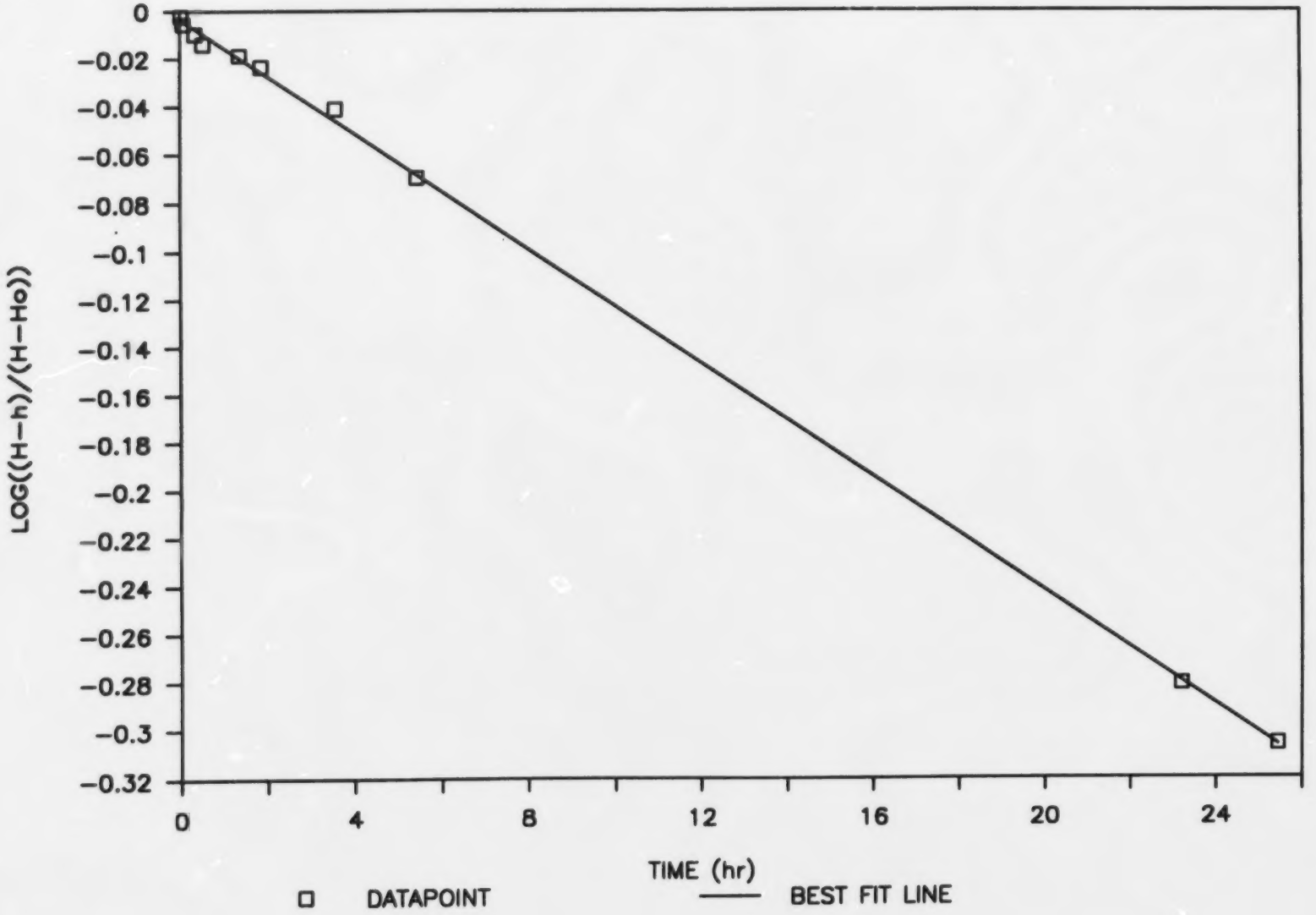
NANTICOKE PIEZOMETER #5-6



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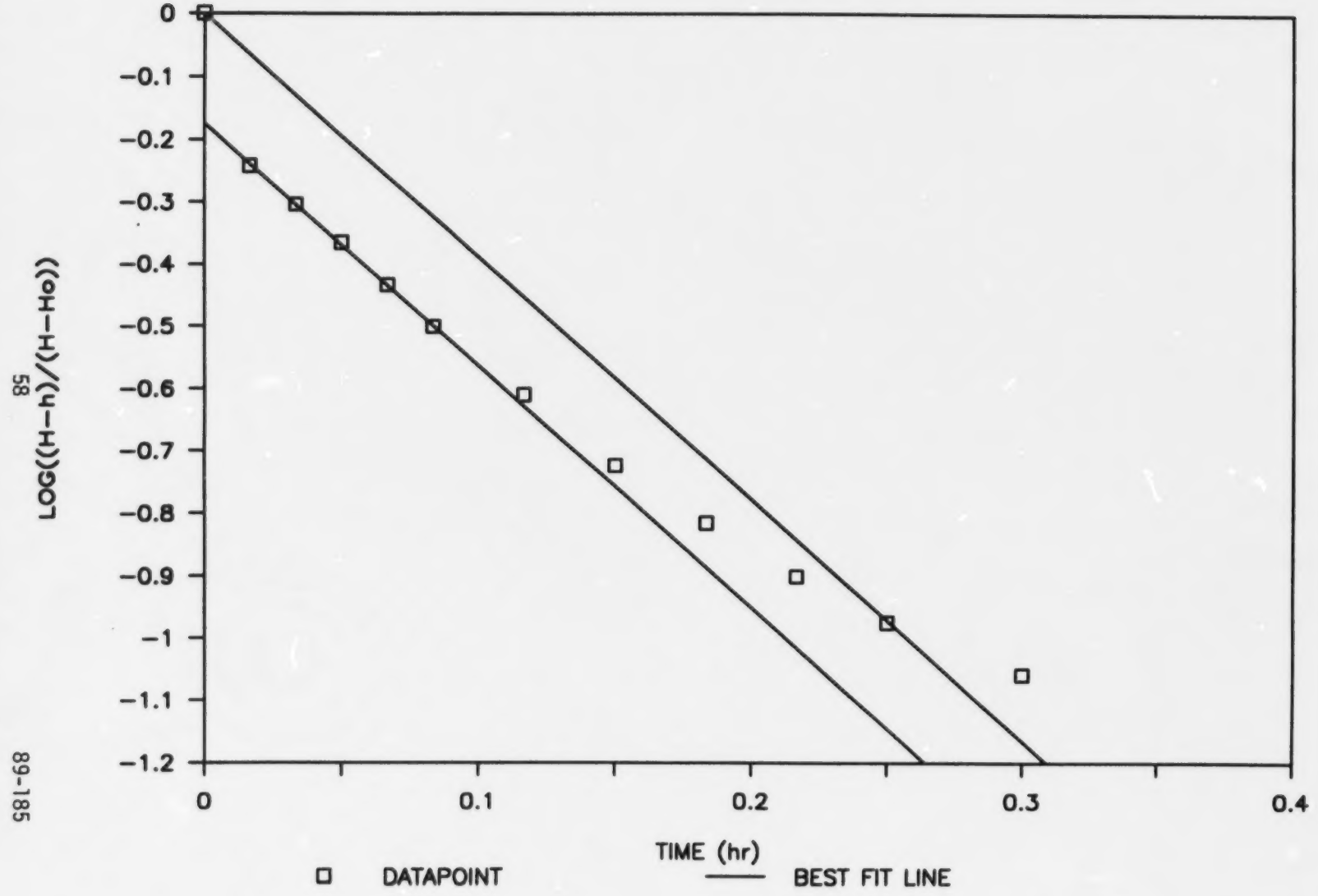
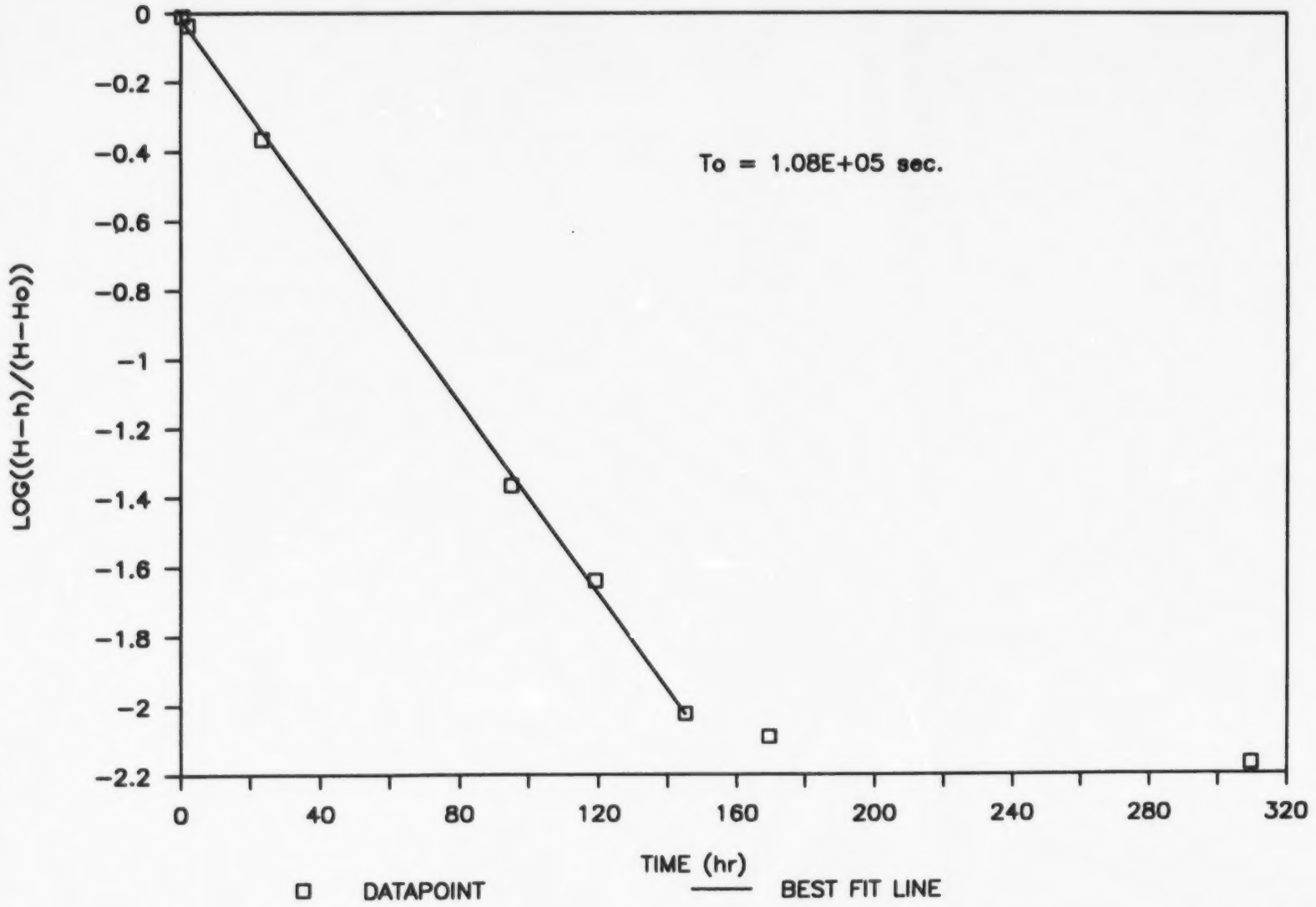
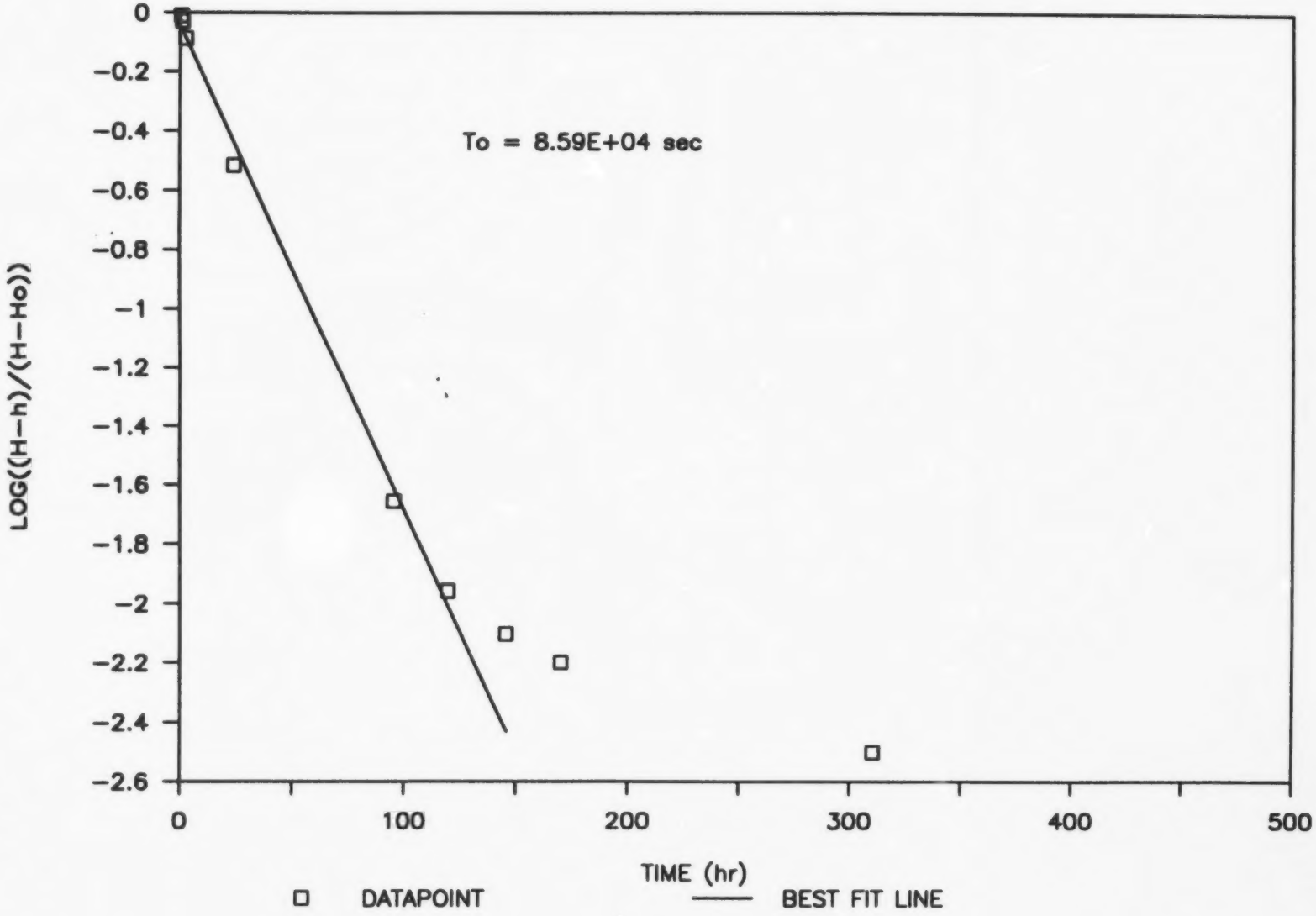
NANTICOKE PIEZOMETER #6-1



NANTICOKE PIEZOMETER #6-2



NANTICOKE PIEZOMETER #6-3



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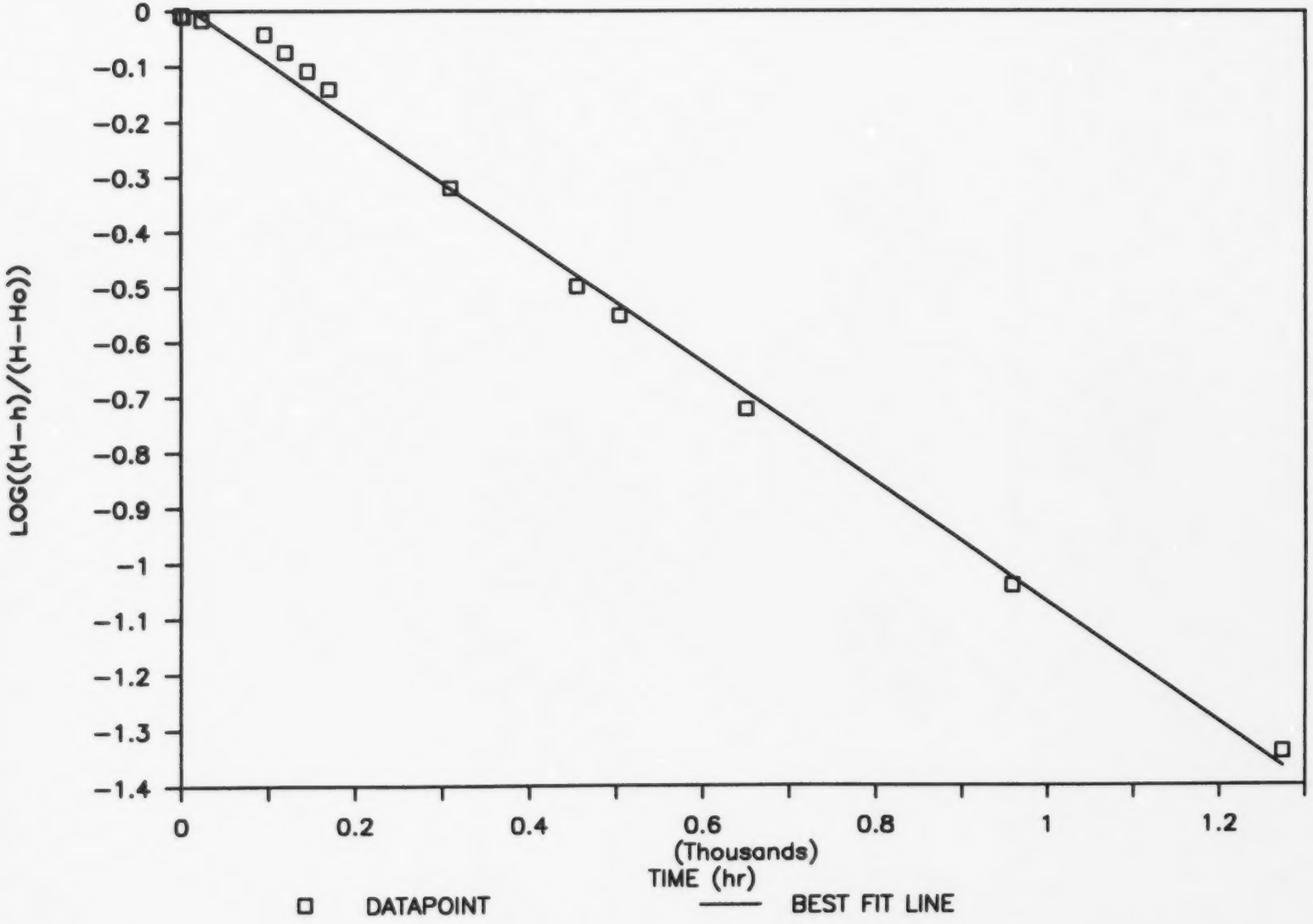
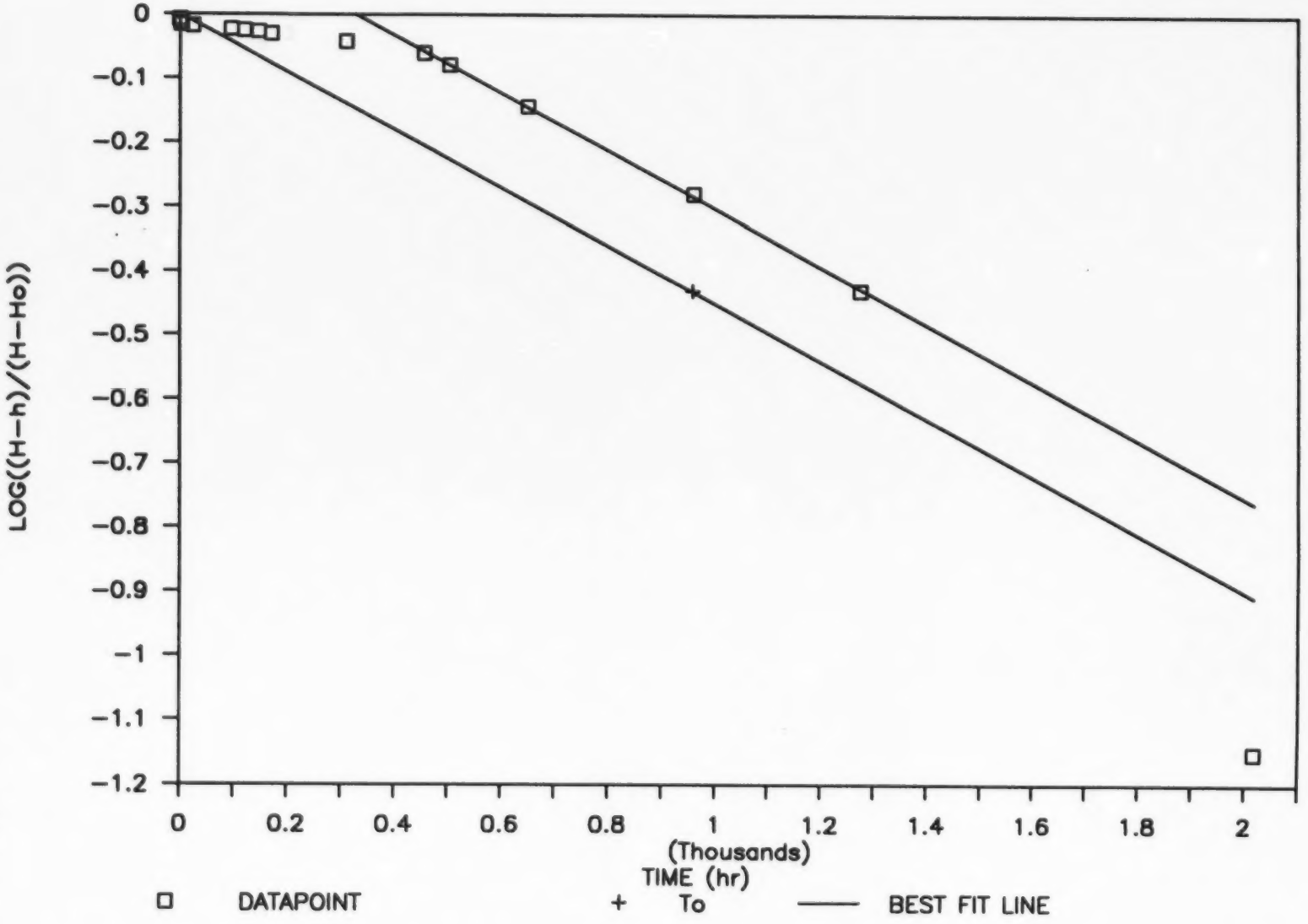
NANTICOKE PIEZOMETER #6-4



NANTICOKE PIEZOMETER #6-5



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NANTICOKE PIEZOMETER #6-6